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DUST STORMS FROM OWENS AND MONO VALLEYS, CALIFORNIA

by
Pierre Saint-Amand, Larry A. Mathews, Camille Gaines, and Roger Reinking

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NAVAL WEAPONS CENTER
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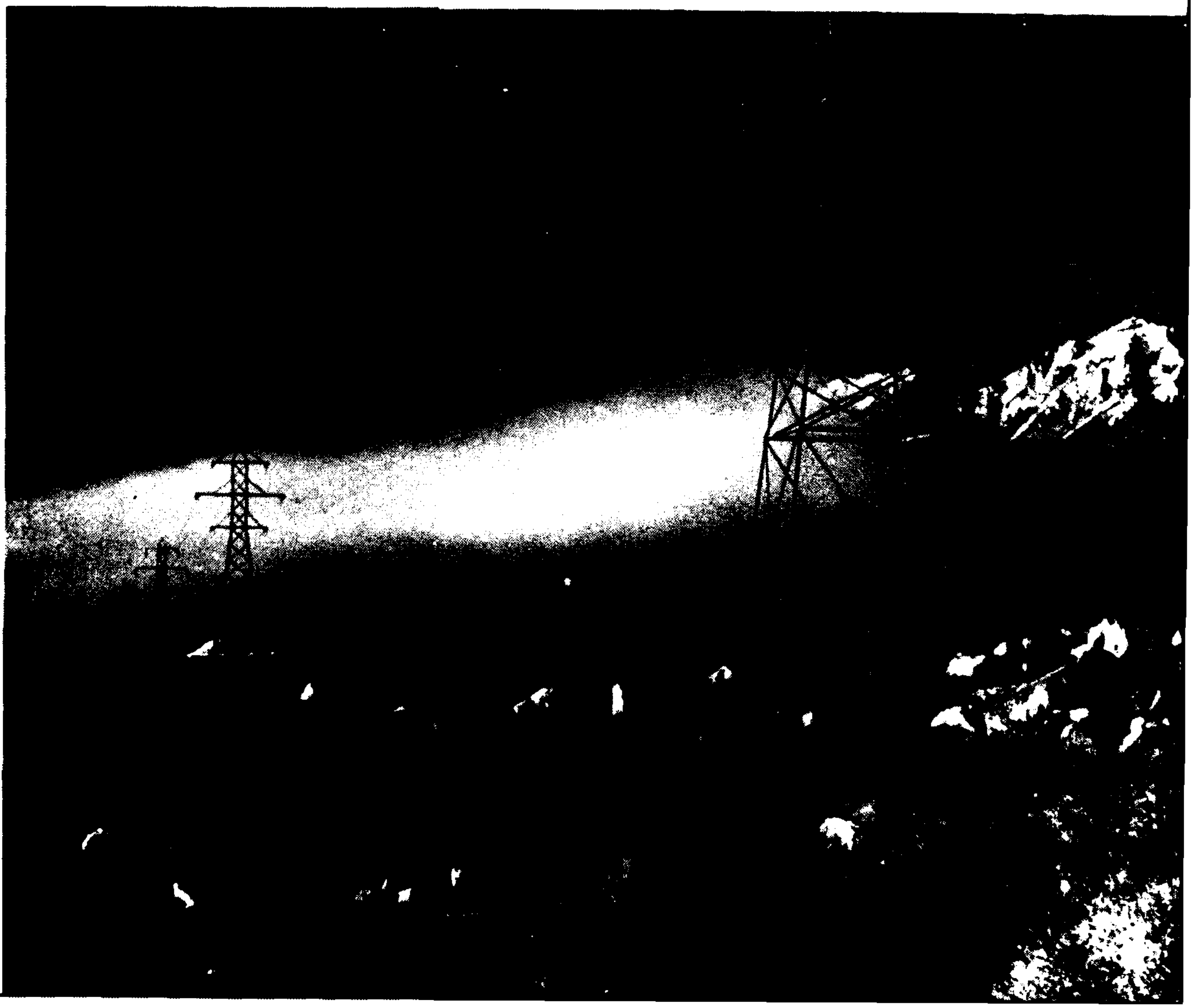

Naval Weapons Center

FOREWORD

This report discusses the periodic dust storms that arise from the surface of Owens Lake, a dry lake located in the Owens Valley some 50 miles north of the Naval Weapons Center, and from the area around Mono Lake, 100 miles north of Owens Lake. The report considers the causes of the dust storms and suggests some treatments to alleviate the problem.

The work upon which this report is based was begun in 1975 and completed in 1986. It is hoped that the material contained herein will prove helpful not only to those whose interest lies in controlling the dust storms from Owens and Mono Lakes, but also to researchers in other parts of the world who are faced with the problem of putting marginal land to productive use.

This report has been reviewed for technical accuracy by Dr. R. L. Hoffmann.

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(U) This report discusses the dust storms that periodically rise from playas at Owens and Mono Lakes in California, the causes and effects of these storms, and some treatments to alleviate the problem.

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CONTENTS

EXECUTIVE SUMMARY

Climatic change, local consumptive use of water, and export of surface and ground water are dessicating Owens Valley. Dust storms originate from dry portions of the saline playa of Owens Lake and to a lesser extent from the surrounding shores and from the valley floor. The dust storms usually occur in late fall, winter, and early spring. The dust storms are worse following winter rains, snow, or in years in which water has been added to the usually dry lake. As many as 10 major dust storms per year are caused by northerly winds aligned with the axis of the valley, usually at passage of a low pressure trough. Dust from these storms has been observed on satellite photographs for at least 250 kilometers south of Owens Lake and covering areas of over 90,000 square kilometers. More frequent, but often less severe, storms occur whenever the winds blow in any direction.

Visibility during such storms is often reduced to 1 kilometer or less. Atmospheric loading has exceeded 1.5 metric tons per square kilometer, and particulate concentrations have reached 2,600 micrograms per cubic meter of air 100 kilometers to the south of Owens Lake. The particles are much smaller than those of most desert dust and sand storms. Over 90% of the particles are less than 0.1 micron in diameter. They consist of alkali chlorides, carbonates, and sulfates as well as silts and clays. The small size of the particles makes retention by the lungs a health hazard.

The fine dust suspended in the storms arises from a solanchak developed on the surface of the playa by the growth of alkali crystals that disrupt the clays and silts. The growth of the crystals is caused by upward capillary and osmotic transport of dissolved solids from the groundwater table. During hot weather, a hard crust develops. In cool weather, the carbonate and sulfate salts gain water of hydration and expand. Subsequently they lose water of hydration, decrease in volume, and become anhydrous, amorphous masses of finely divided light and fluffy powder leaving the dissaggregated clays and the alkali free to be blown by the wind.

There are many potential approaches to the problem of dust blowing from Owens and Mono Valleys. These range from a complete hands-off approach to the installation of a system of polders combined with water-table lowering. Certain of these treatments may have application in desert playas both in this country and in other parts of the world.

INTRODUCTION

Dust from the bed of Owens Lake and from the floor of Owens Valley is often picked up by winds in excess of 15 knots, regardless of wind direction. Small dust storms are common. Gigantic dust storms, created when a north wind blows, carry dust southward for hundreds of kilometers. These storms interfere with air and ground transport, curtail operations at the Naval Weapons Center and Edwards Air Force Base, and disrupt activities in the nearby desert communities. Dust from such storms, when scavenged by rain, has fallen in Orange County. The storms are worse in years when there has been rain, snow, or flooding of the dry lake surface. A condition similar to that in Owens Valley is developing at Mono Lake. Figures 1 and 2 show the locations. A previous paper (Reinking et al. 1975) called attention to the situation. This document explores the causes and suggests ameliorative measures.

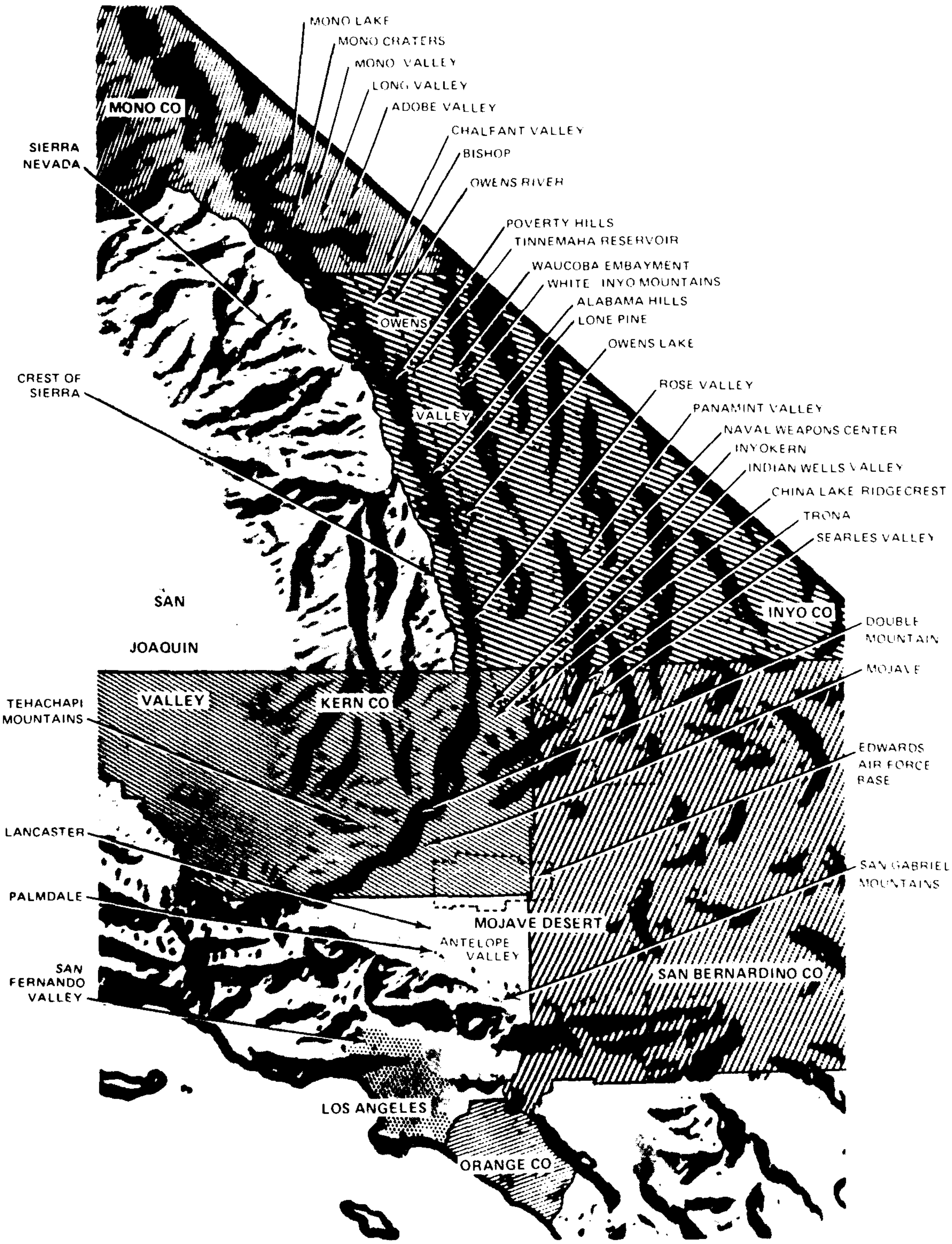


FIGURE 1. Regional Map Showing Locations Referred to in the Text.

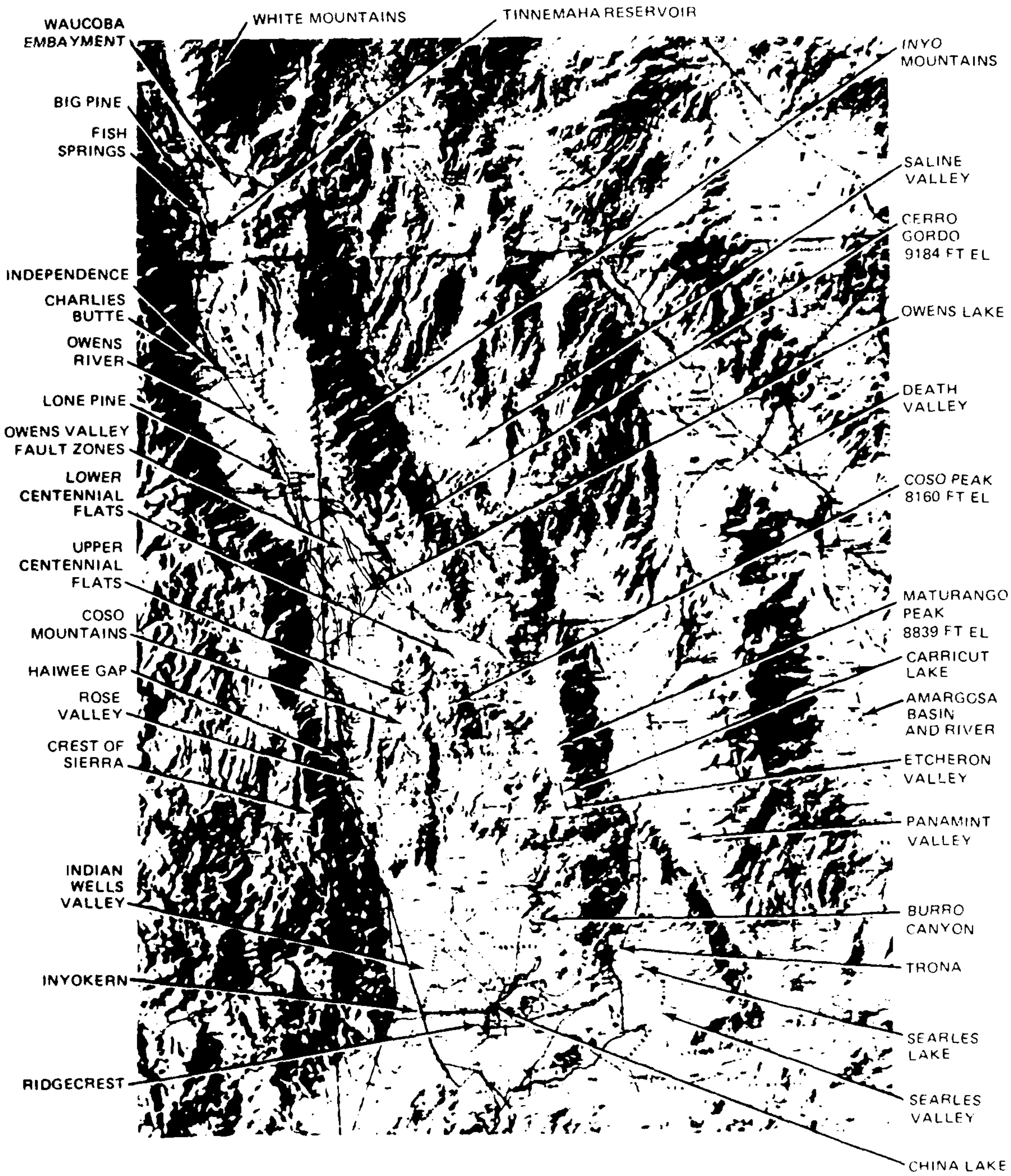


FIGURE 2. Local Map Showing Locations Referred to in the Text.

BACKGROUND

GEOGRAPHY

Owens Valley (Figure 3) is a north-northwesterly trending trough in eastern California, bounded by the Sierra Nevada on the west and the White-Inyo Mountains on the east. The lowest point of the valley is at 3,552 feet above mean sea level (MSL) on the surface of the Owens Lake playa, which serves as a sump for the rest of the valley. The valley floor rises to 4,120 feet at Bishop, where the trough widens to several tens of kilometers and bifurcates. To the north the trough is called Chalfant Valley; to the north-northwest the trough is called Long Valley.

GEOLOGY

At the end of Pliocene, about three million years ago, Owens Valley was a shallow indentation in an erosion surface of low relief that extended from north of the present site of Bishop, southward to the Mojave Desert block. This protovalley, filled with a lake or lakes, deepened during early Pleistocene as the Sierra Nevada and the Inyo Mountains grew (Walcott 1897; Spurr 1903; Reid 1908; Trowbridge 1911; Zbur 1963; Axelrod 1962; Bachman 1974 and 1978; and Saint-Amand and Roquemore 1977).

The western side of Owens Valley is festooned with coalesced alluvial fans that reach from the rocky slopes of the Sierra to the central portion of the valley (Figure 4). The alluvial cones on the eastern sides are less well developed and mainly confined to the mouths of canyons; the steep mountain slopes often reach the flat floor of the valley. The valley is filled with fanglomerates that taper to, and interfinger with, a clay plug in the central and eastern portions of the valley (Figure 5). The maximum depth of fill, as measured by geophysical techniques, is at least 6,000 feet (Pakiser et al. 1964). Pittsburgh Plate Glass Co. drilled a well to a depth of 6,000 feet, near its plant on the western shore of the lake, without striking either bedrock or a salt body. Detailed stratigraphy is available only for one well (Smith and Pratt 1957).

FIGURE 3. Owens Lake (View Looking East).

FIGURE 4. Frontal Scarp of Sierra Nevada (View Looking West)

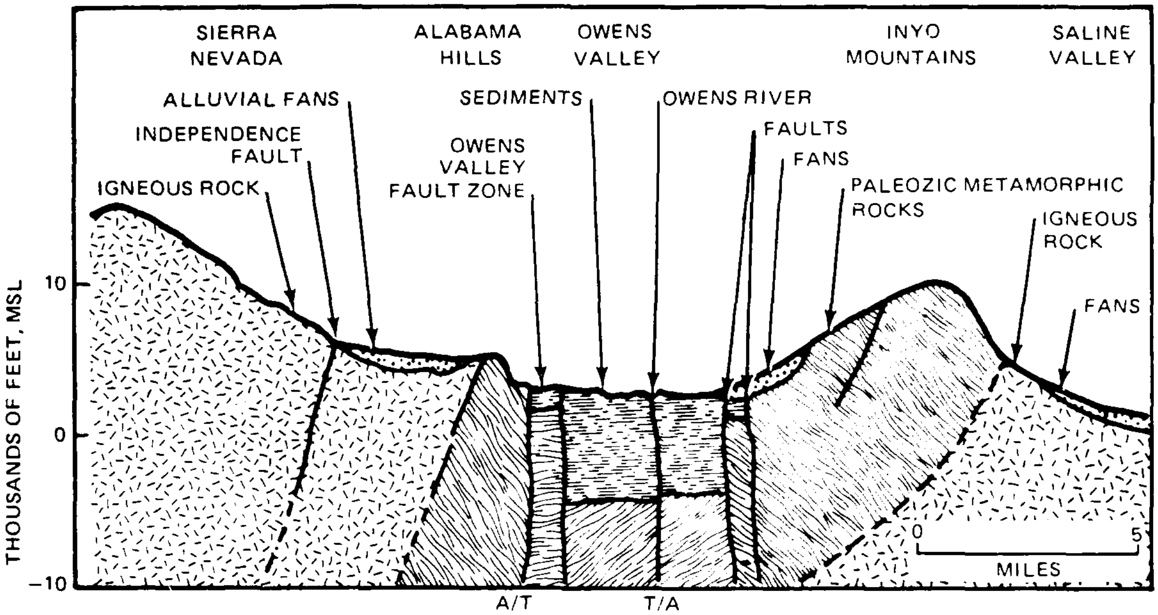


FIGURE 5. Cross-Sectional View of Sierra Nevada, Owens Valley, and the Inyo Mountains at the Latitude of Swansea (After Knopf, 1918).

The valley is tectonically active, as attested by the 1872 earthquake on the Owens Valley Fault. The western side of Owens Lake, then full of water, dropped 1 meter with respect to the eastern side (Hobbs 1910). The older shorelines are offset by faulting. The 15,000-year-old Tioga shoreline is multiply offset—an aggregate of 1 mile horizontally and 100 feet vertically on the southeast side of the lake (Figure 6).

PLEISTOCENE LAKES

Owens Valley was intermittently filled with lakes that were part of a chain of lakes that extended from Mono Lake and Adobe Valley to Death Valley (Gale 1914) (Figure 7). These lakes received runoff from the Sierra and local catchment basins during the glacial epochs as well as during some intervening pluvial epochs that did not result in major glaciations. Meltwater from the glaciers and runoff from the mountains carried clays, pyroclastic materials, and other debris into the lakes. At times, the runoff was charged with solids dissolved from freshly erupted volcanic rocks in Long Valley and in Owens Valley.

SHORELINES

Prominent shorelines at an elevation of 3,880 feet msl, 328 feet above the present lake surface, are incised by small gulleys, partially obscured with windblown sand and offset by faults but otherwise little altered (Figure 8)(see Carver 1967). Fans from the Inyo Mountains have partially obscured the eastern shorelines. The shorelines may be traced from Swansea on the eastern side of the lake (Figure 9) into Haiwee Gap, where they are lost in the incompetent beds of the Coso Formation. On the western side, shorelines reach to the northern end of the Alabama Hills.

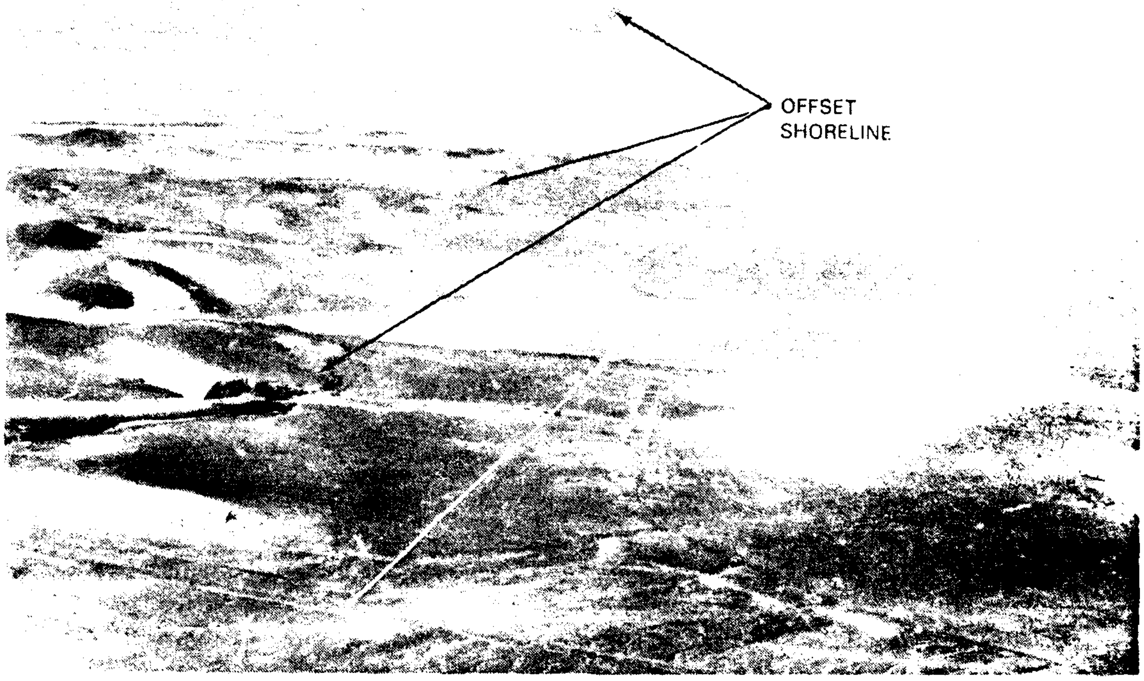


FIGURE 6. Offset Shoreline Near Southeast Corner of Owens Lake (View Looking Southwest).

The higher shorelines are 180 feet above the present outlet of the valley, which is at 3,700 feet. Downcutting of the drainage channel into Rose Valley must have happened rapidly, because only a few indistinct shorelines are visible between the 3,880-foot set, which is estimated to be late Wisconson (Tioga) in age (probably 15,000 to 16,000 years ago), and the younger shorelines, developed at the turn of this century, at 3,590 feet.

The spillway of the valley is about 150 feet above the lowest point on the lake bed. The terminal drying must have happened rapidly before a channel could be cut deeper into the gap at Haiwee. Possibly the lake level was abruptly lowered by a tectonic down-dropping.

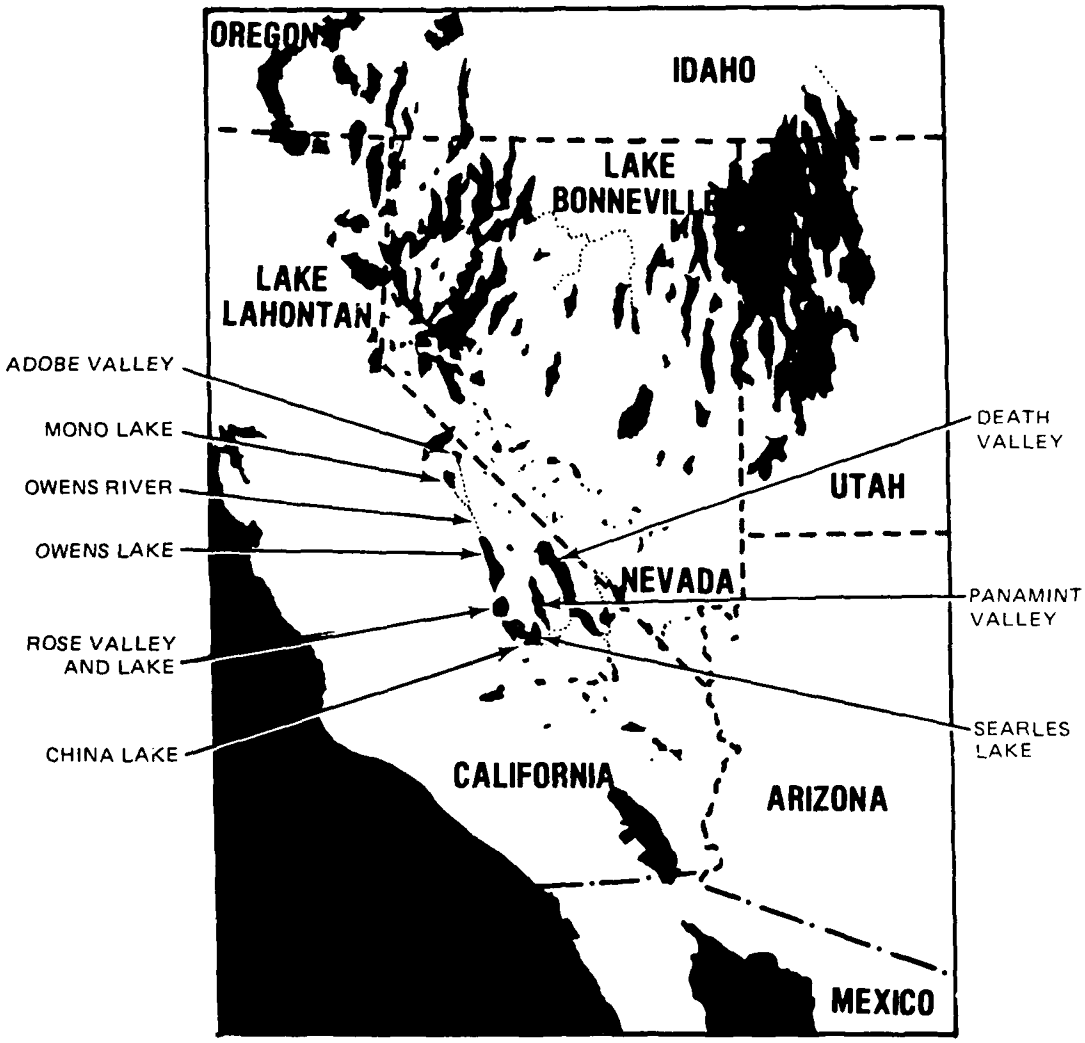


FIGURE 7. Map of Pleistocene Lakes and Drainage.

LACUSTRIAN CLAYS

Lacustrian clays are exposed on the valley floor as far north as Bishop, but the 3,880-foot stand of the lake would have reached only to the vicinity of Tinemaha Reservoir. The Poverty Hills are partly covered by tilted mid-Pleistocene lacustrian sediments, dated by Cleveland (1958) on the basis of diatoms. Bachman (1978) has mapped Mid-Pleistocene lakebeds well above the valley floor in the Waucoba Embayment.

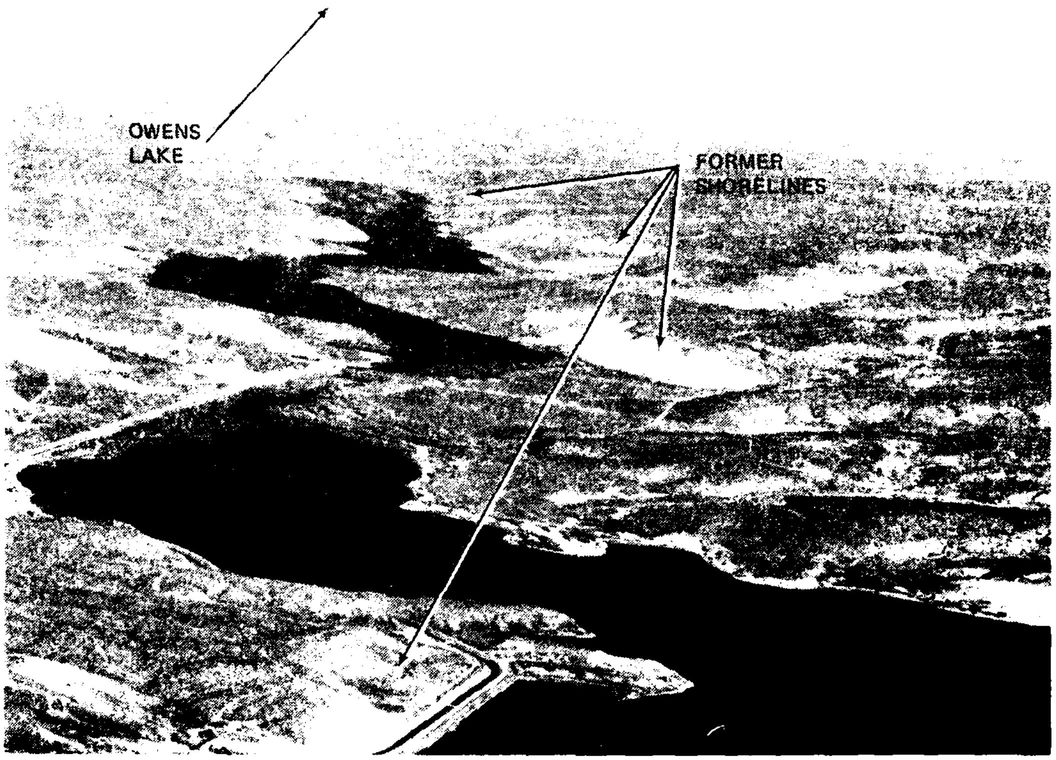


FIGURE 8. Closeup View of Owens Lake Shorelines
(View Looking North)

RAINFALL

The Los Angeles Department of Water and Power (LADWP 1976) reports that the southern part of Owens Valley receives about 4 to 6 inches of rain per year, and the northern part of the valley a little more (Figure 10). Precipitation near the Sierran Crest reaches 20 inches per year. The Inyo and White Mountains get between 8 and 12 inches. The precipitation in the valley is sporadic. Some years may pass without rain or snow, but occasionally, large thunderstorms cause flash flooding and produce debris flows. The present drainage area is 2,900 square miles. The precipitation during the epochs in which the whole lake was full of water must have been 3 to 5 times what it is now, unless the climate was much cooler (Smith and Street Perrott 1983). At its highest stand, Owens Lake maintained a near-equilibrium level long enough to develop the conspicuous shorelines on the eastern and southern sides of the lake. During progressive climatic changes, the lakes dried and the overflow from one valley to the next ceased.

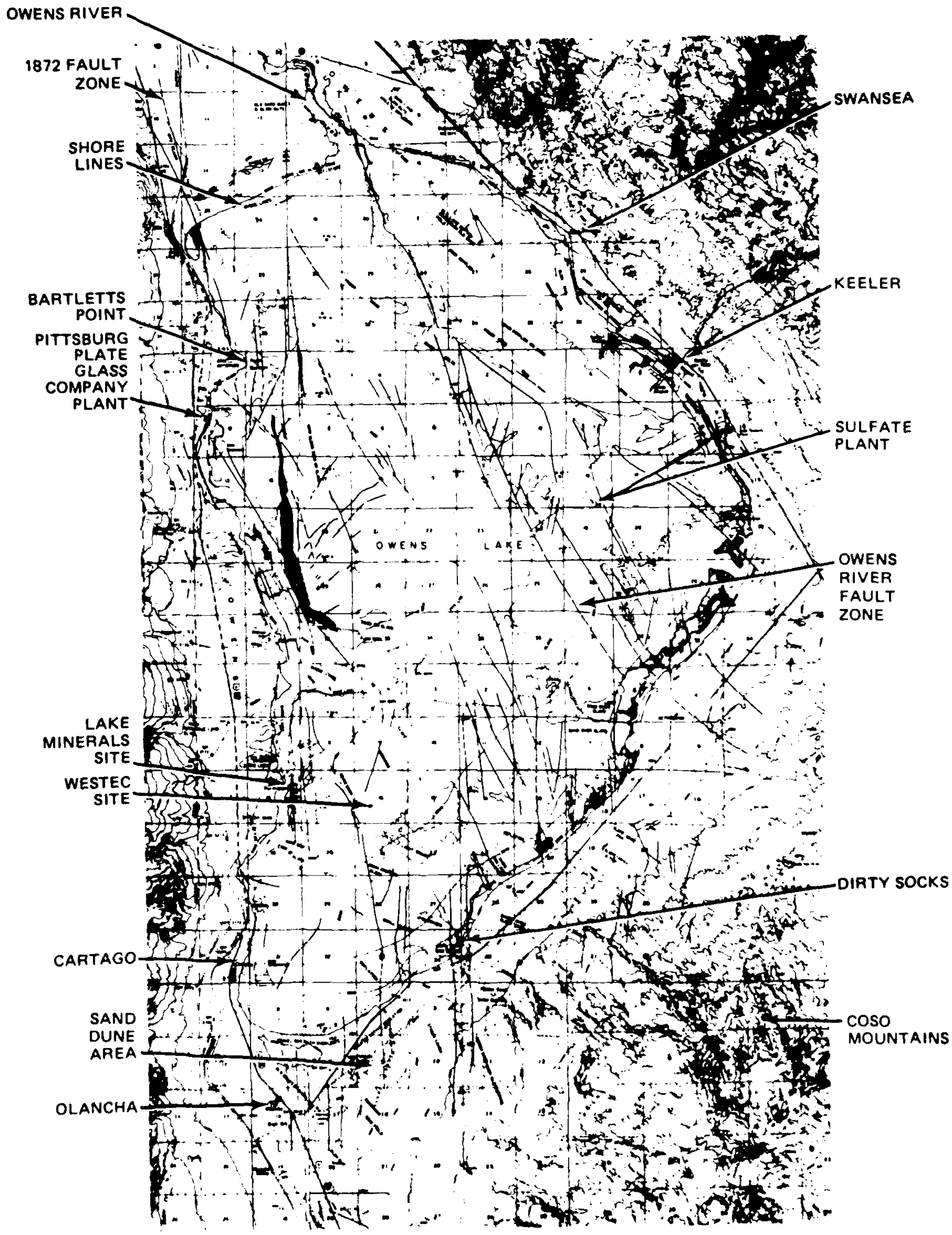


FIGURE 9. Map of Owens Lake.

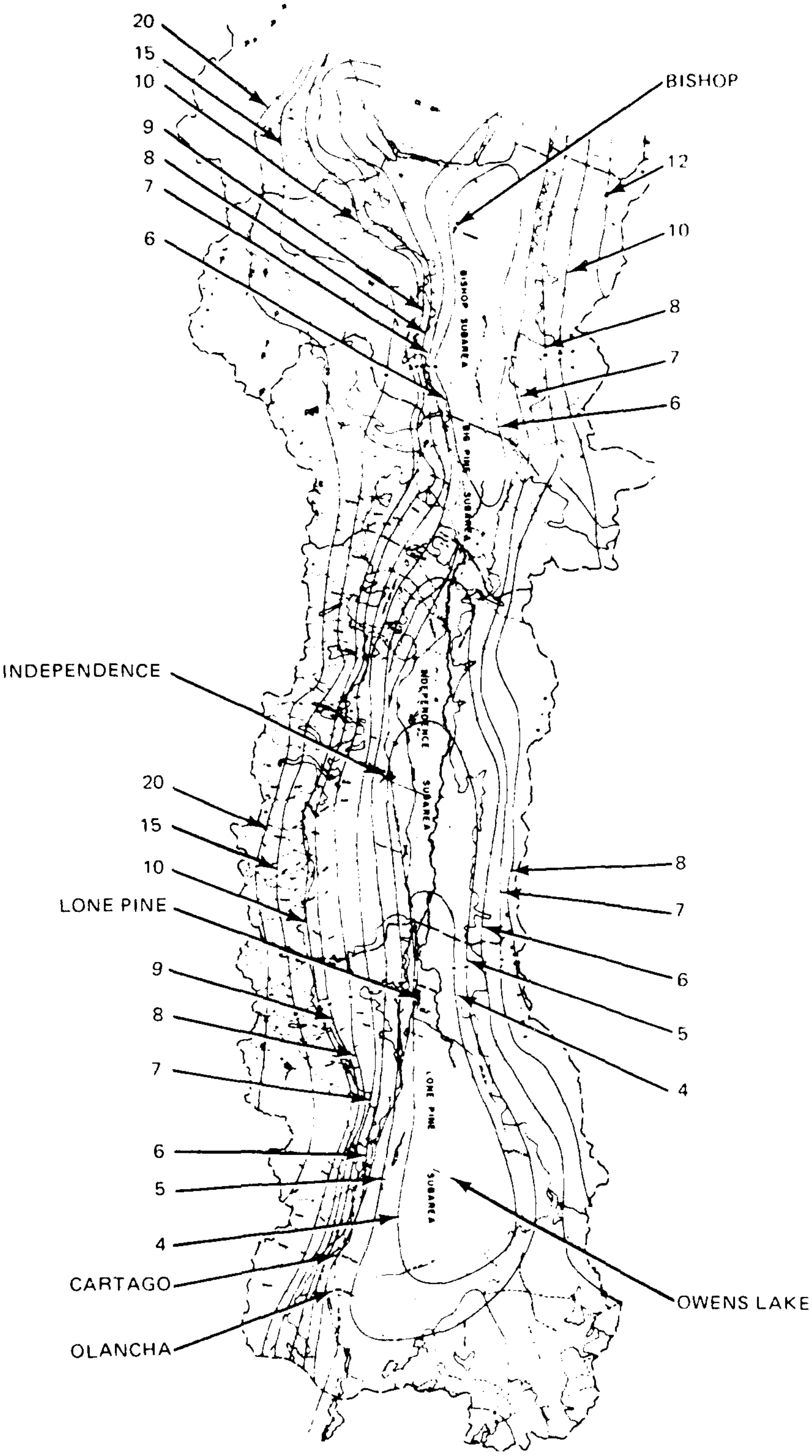


FIGURE 10. Rainfall Map of Owens Valley. Numbers indicate inches of rainfall at contour lines.

DESSICATION OF OWENS LAKE

Although Owens Lake probably dried up in hot, dry, interglacial periods, well cores do not indicate that any extensive salt bodies are buried in the sediments. The latest dessication was initiated by a natural climatic change and accelerated by local irrigation and by export of water. The story of the water export, well known in the area and still fraught with some emotion, is told from quite different points of view by Chalfant (1933), Nadeau (1950), and Kahrl (1982). We here recount, as well as we can reestablish them, only such facts as bear on the environmental problems.

ADVENT OF AGRICULTURE

Between 1840 and 1890, the rainfall of coastal Southern California decreased (Lynch 1931, p. 3, fig. 1). In 1862, 1863, and 1864, many stockmen and farmers left that area and moved to the mountains and to Owens Valley, where surface water was abundant (Dasmann 1968). At that time, Owens Valley had numerous springs and artesian wells. While the mines at Cerro Gordo operated, two small steamers plied the waters of the lake between Keeler and Cartago (Krauter 1959). Farmers withdrew irrigation water from Owens River and subsidiary streams. Over 40,000 acres were extravagantly irrigated. By 1904 some 297,000 acre-feet were being diverted with an average depth of application of 7.5 feet per year (Lee 1906, p. 23 et seq.) leaving about 65,000 acre-feet to flow to the lake. The equilibrium requirements for evaporation for the 110-square-mile lake would be at least 350,000 acre-feet per year, depending on weather. A good deal more land was placed in pasturage, which, although not irrigated, used more water than the native xerophytes and thus added to the water burden.

In 1917 Thalia Weed Newcomb conducted an inventory of Inyo County; 41,000 acres were in alfalfa, 8,000 acres in wheat, 1,700 in barley, 2,560 in oats, 6,000 in clover, 750 in beans, 1,500 in potatoes, and 400 in sugar beets. Orchards were well developed; there were an estimated 114,000 apple trees, 28,500 peach trees, 17,600 pear trees, and some berries. In 1910 the population of Inyo County, mostly in the Owens Valley, was 6,974; in 1917 it was about 8,000. Farming and ranching continued on a large scale until they tapered off in the 1920s. The local consumptive use of water exceeded the evaporative demands of Owens Lake and eventually dessicated the lake during periods of drought, even before the export of water (1913) to Los Angeles.

EXPORT OF WATER

In 1904 the Department of Water and Power of the City of Los Angeles obtained lands and water rights in Owens Valley. An aqueduct, the greatest engineering feat of its day, was built to convey the water to the San Fernando Valley. Water first arrived in the San Fernando Valley on 5 November 1913 (Nadeau 1950); full flow has been maintained since 1926 with but minor interruptions. In 1918, the LADWP started sinking wells into Owens Valley to withdraw groundwater. Between 1930 and 1969, the Department acquired water rights to all the headwaters of the Owens River and diverted all the major streams in Long Valley and Mono Basin into the Los Angeles water system. A second aqueduct was built to export more water to the Los Angeles area.

CHANGES IN LAKE LEVEL

Natural causes have created great fluctuations in the water level in Owens Lake. Smith and Pratt (1957) give core logs on a 920-foot well in the central part of Owens Lake. The upper 740 feet show a continuous series of clays and silts with no buried saline deposits. Smith and Street-Perrott (1983, p. 198) conjecture that the lake had not dessicated naturally for several hundred thousand years. The drainage was probably through-going during most of the time in which these sediments were deposited. However, some episodic drying must have taken place, because fossil sand dunes are found in the northeastern corner of the lake bed and on both sides of Owens River near the lake. The presence of artesian wells within the playa area indicates that extensive layers of high permeability are present within and beneath the clays. These were probably deposited during dry epochs. Moreover, ample evidence has been developed to show that China Lake and Searles Lake both dried up several times during the Pleistocene.

During the Tioga Glaciation (Late Wisconson) the lake was filled to the 3,880-foot contour and covered 240 square miles. The lake drained through whatever dammed it at the level of those shorelines and eroded the outlet down to a level of 3,760 feet. This overflow appears to have been dammed in turn by alluviation from the sides. Shortly thereafter, the lake ceased to drain into Rose Valley. Smith and Street-Perrott (1983) estimate, based on the amount of salines on the present lakebed, that this drainage must have ceased about 2,000 years ago. Gale (1914) estimates between 3,500 years and 4,200 years. Langbein (1961) critiques this technique. Since the spillage ceased, more water has evaporated than has been received. By 1872 the lake had dropped to a level of 3,597 feet and covered an area of 112 square miles (Gale 1914, citing Loew 1876).

During the period of intensive farming, whilst a general drought persisted in California, the level of the lake dropped to 3,567 feet in 1905. The lake then began to rise, and by July 1911 it had reached 3,578 feet. On the basis of data from Gale (1914), Lynch (1931), and Newcomb (1917), it seems that fluctuations in the amount of precipitation contributed more to the changing levels of the lake than did the amount of irrigation. In 1917, with the extensive use of water for irrigation and the removal of water by the LADWP, the level of the lake was still quite high due to a period of above-normal rainfall. The city increased its removal of water during drought years, and the lake completely dried up in 1926. From that time to the present, water has reached the lake intermittently when damage occurred to the aqueduct or when a surplus of water made discharge to the lake desirable.

Figure 11, reconstructed from data furnished by the LADWP and from reports by Gale (1914) and Lee (1913) shows the history of the lake level. Concomitant with the drying of the lake, the artesian sources of water, and most of the naturally flowing springs, such as Fish Springs, have dried up (Tolman 1937, p. 194). Artesian wells still exist around and on Owens lake, and numerous springs feed the playa from the sides (Figure 12).

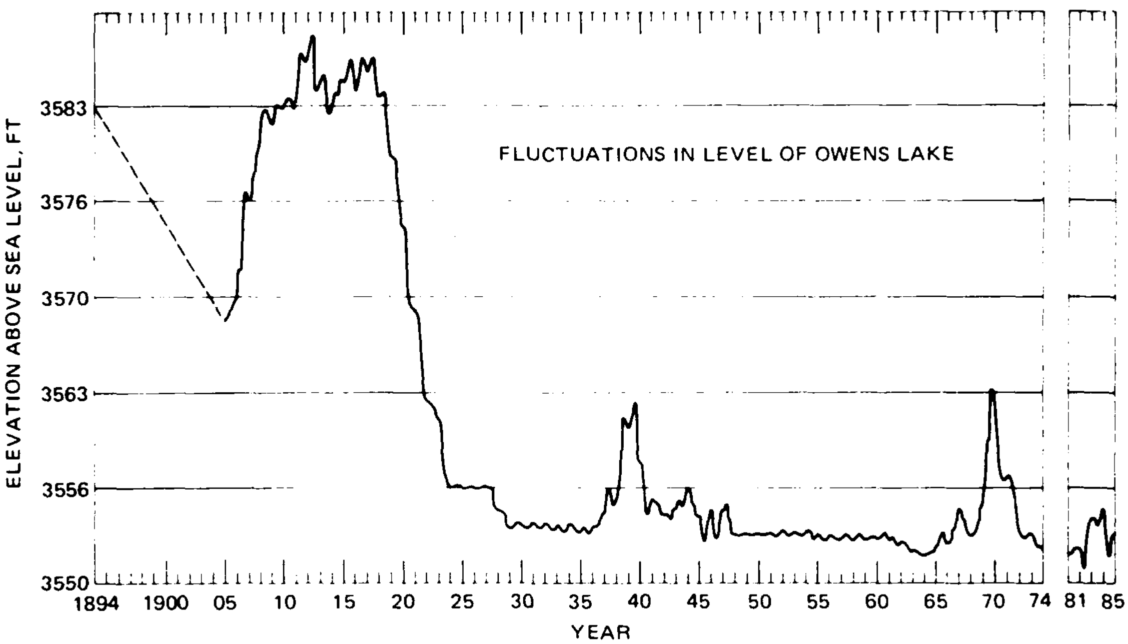


FIGURE 11. Changes in Level of Owens Lake From 1894 to 1985.

FIGURE 12. Dirty Socks, an Artesian Well on the South Side of Owens Lake. To the left, vegetation grows around natural springs.

HISTORICAL ECOLOGY OF OWENS LAKE

A few descriptions of the ecology of the lake in the 1800s survive. Capt. J. W. Davidson, in his report on the 1859 expedition to Owens Lake (Wilke and Lawton 1976), is one of the first men to describe this region. He mentions that the Indians used the alkali flies of Owens Lake as a food source. Apparently the Indians gathered the larvae as they were blown ashore. Guy C. Earl, Jr. (1976, p. 61), in the posthumous publication of his father's memoirs, mentions that the Indians used the flies as food. Guy Earl, Sr., was a boy at the time of the great earthquake in 1872. He says "In the extremely alkaline water of Owens Lake no animal life is to be found except an insect (of about the size and appearance of a housefly) called locally 'lake flies,' but which I am told is in reality a kind of shrimp. These insects breed in masses several feet wide and a foot or more thick. The Paiutes dried them for food, carrying them away in sacks to their rancherias in different parts of the Enchanted Valley. I have often eaten them at the Indian camps."

Loew (1876) says that large quantities of "algous or fungoid" plant material floated upon the lake in small globular masses of a whitish or yellowish green. These apparently served as aircraft carriers for hordes of alkali flies (Ephydra) whose larvae inhabited the lake waters. Chatard (1890) says that the water swarmed with alkali shrimp (Artemia). By 1906 Willis Lee found that the conditions had changed since these earlier observations (Lee 1906). In 1904, the lake was 16 feet lower than in 1894, and although larvae were still present, the flies were failing to develop. Dr. Noah Wrinkle, superintendent of the soda recovery works at Keeler, as cited by Lee (1906, p. 21), opined that the larvae were failing to develop because of the increasing salinity, whereas at Mono Lake they were as numerous as ever. Today, only a few flies are found around Owens Lake, usually in places where an abandoned artesian well or a spring dilutes the saline waters.

SALINITY

According to Gale (1914, p. 258 et seq.), the weight percent of the total dissolved solids in anhydrous form ranged from 6% in 1876 to a high of 21.4% in 1905. This material is, of course, the dissolved solids that were in the lake when it ceased to spill to the south, and the solids that have been brought in by the Owens River since then, concentrated by evaporation. When the water body is but a foot or so deep, it occupies only a few square miles of the sump on the western side of the lake, where the land level was lowered during the earthquake of 1872 and its predecessors. The liquid at such time is saturated, and crystals grow on the bottom and on the surface. When the lake bed is dry, enormous deposits of trona, mirabilite, natron, burkeite, thenardite and similar evaporites are found on the western reaches of the lake.

DESSICATION OF MONO LAKE

Pleistocene Lake Mono (Figure 13) was formerly 650 feet deep. It reached a maximum level of 7,165 feet, as shown by abandoned terraces, and occupied about five times its present area (Russell 1889, p. 229). Precipitation was at least four or five times that of today. Smith and Street-Perrott (1983, p. 198) report that drill cores examined by Lajoie revealed no saline layers even below the Bishop Tuff, which they take to mean that the lake had not dried up

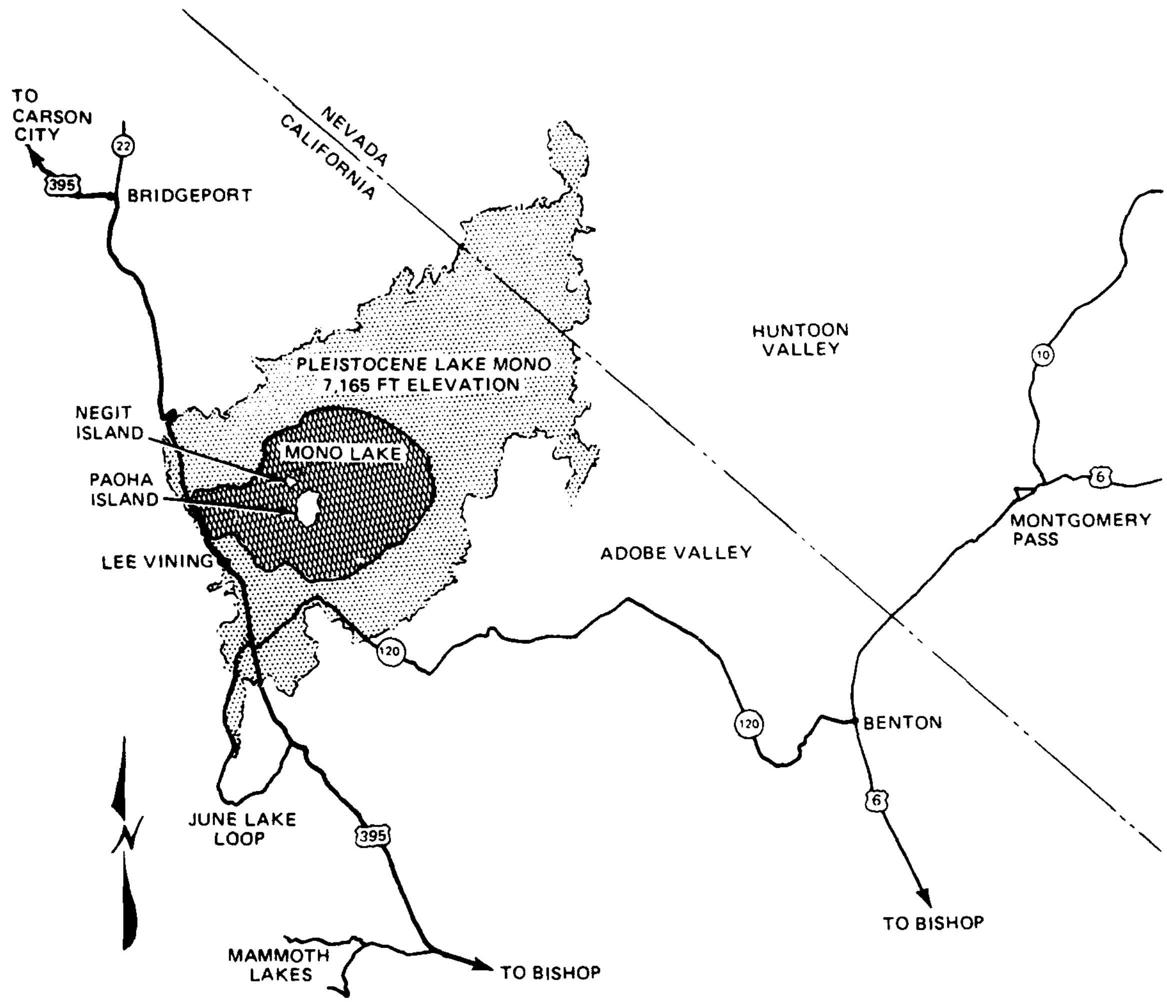


FIGURE 13. Map of Mono Lake.

completely for at least 700,000 years. Following the end of glacial activity, the level of Lake Mono began to fall. In 1883 the level of the lake was at 6,410 feet. By 1919, after a long perod of abundant rainfall, it had reached a high of 6,429. During the drought years of the mid-1920s and 30s, the lake level fell to 6,416 (Stine 1981). Figure 14 shows abandoned shorelines of recent vintage around Mono Lake.

LAKE ADOBE

At its peak, Mono Lake overflowed into Adobe Valley. Lake Adobe, in turn, overflowed into Owens Valley (Figure 13). Lake Adobe refilled about 8,000 years ago and again about 4,000 years ago, but is now dry (Batchelder 1970).

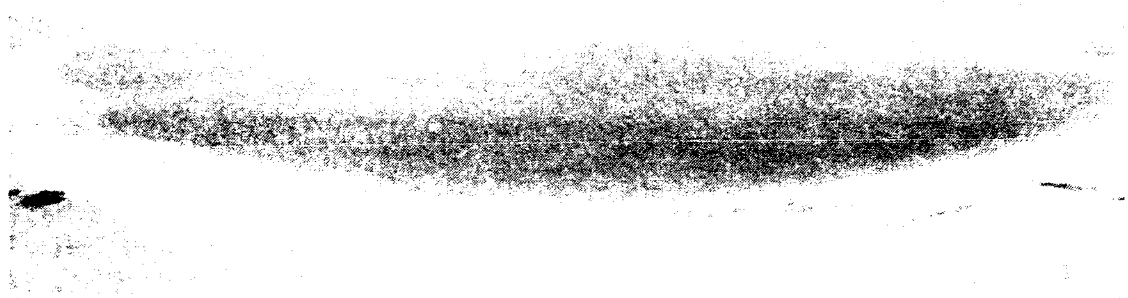


FIGURE 14. Mono Lake Shorelines.

EXPORT OF WATER FROM MONO LAKE

LADWP took its first water from Mono Basin in 1941. A tunnel driven through the Mono Craters carries the water into the Owens River and thence to Los Angeles. The second aqueduct was completed in 1970, and about 100,000 acre-feet of water per year has been exported since then. The continued drop in the level of the lake is mainly due to this export of water, although climatic conditions have also contributed.

EXPOSED LAKE SURFACE

Loeffler (1977) developed a model that predicts that the level of Mono Lake will stabilize at 6,223 feet just after the year 2050, if the present water export and climatic conditions continue. Ten square miles of barren lake bed had been exposed by 1964 (Figure 15).By 2050, an additional 43 square miles will be exposed.

Just how much exposure will actually take place depends somewhat upon legal decisions concerning the amount of water that can be exported from that valley. Many groups wish to see the lake level remain as high as possible, but this would be a grave loss of domestic water vitally needed in Southern California.

The newly exposed lakebed is covered with a fluffy alkaline crust produced by evaporation of the saline lake waters. This gives rise to dust storms whenever the surface wind exceeds 15 knots (Figure 16). Kusko and Cahill (1984) discuss the nature of the dust. The region will be a source of dust for centuries to come. Much of the material that follows, developed for Owens Lake, also applies to Mono Lake, although some differences in climate and chemistry will require modification of the arguments.

FIGURE 15. Mono Lake Levels (Past and Projected).

FIGURE 16. Dust Storm From Mono Lake.

DESCRIPTIONS OF OWENS LAKE DUST STORMS

SEASONAL OCCURRENCE

Severe dust storms from Owens Lake occur most often during dry windy periods in late fall, winter, and early spring. Dust storms during hot weather are rare and never large, even with winds strong enough to move coarse sand. As many as ten dust storms each year reach the Indian Wells Valley. Figure 17 shows one such storm advancing upon Ridgecrest.

METHODS OF OBSERVATION

Dust storms have been observed from ground level in Owens Valley, on the floor of the dry lake, from the ground at China Lake, and from points in between. Observation flights were made during some of the storms, satellite photographs were studied, and cameras were mounted on the surrounding hills to record the storms. Samples of the dust were obtained with high-volume samplers, and measurements were made of particle size. Laboratory studies were done on the behavior of the saline components, and models were constructed using lake-bed clays and brines. We visited the playa monthly in 1985.

FIGURE 17. Dust Storm Advancing on Ridgecrest From the North.

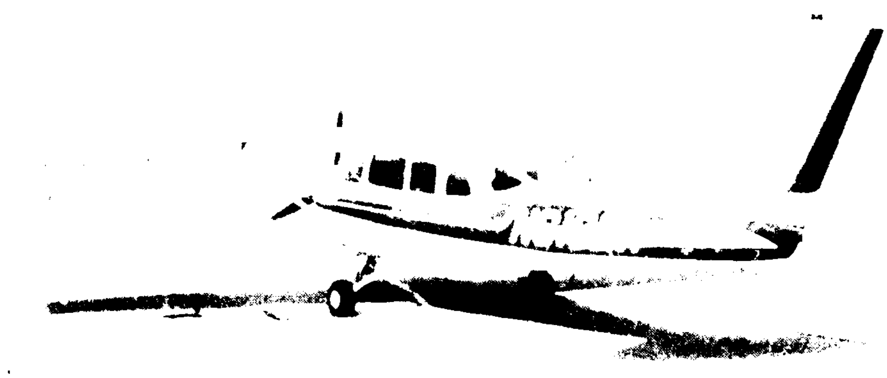
CHARACTERISTICS OF MAJOR STORMS

During a storm, the dust rises to considerable height. Dust at Haiwee Gap frequently reaches the Sierran Crest to the west, some 4,800 feet above the ground. On 22 January 1985 dust was found at 13,500 feet MSL, blowing over the Sierra toward the San Joaquin Valley. In a series of storms in January and February of 1985, dust, washed from the air by rain, fell as far south as Orange County, where it became a veritable mudfall, damaging paint and wax on vehicles and causing alarm to the public. The major television networks announced that it was a fall of acid rain!

On 25 March 1976, between 0800 and 1000, the first of numerous flights was made from Inyokern to Owens Valley to observe dust storms in progress. Figures 18 and 19 show the aircraft at Inyokern Airport. The Sierra, 3 miles away, cannot be seen. The wind on the ground at Inyokern was from 330 degrees at 30 knots gusting to 40. At 8,500 feet, a dense blanket of dust lay beneath; the ground was indistinctly visible to the north, east, and west. Dust continued to 10,500 feet (Figure 20). The air above and over the Sierra was crystal clear (Figure 21).

Dust obscured the landmarks to the east, with the exception of Maturango and Coso Peaks. To the south, the pall reached the San Gabriel Mountains. Double Mountain was barely visible in the Tehachapi Mountains. The airflow was almost laminar, with but minor turbulence, although the wind was between 100 and 120 knots out of 330 degrees.

FIGURE 18. [illegible]



[illegible]

FIGURE 20. Top of Dust Storm (View From Aircraft).

FIGURE 21. Clear Air over Sierra (Right). Dust Over Owens Valley (Left).

The air over the north shore and central part of Owens Lake was clear and clean. Air descended upwind of, and into, the clear area at a rate of 200 to 300 feet per minute. The lake contained water, streaked by the wind. Dust was blowing along the center and the eastern side of Owens Valley from the vicinity of Tinnemaha Reservoir toward Owens Lake. This dust moved around the eastern side of the lake and across the eastern half of the dry lake bed. The western side of Owens Valley, north of Lone Pine, was free of dust.

Little or no dust came from the northern shores or northern side of the playa. Wind appeared to be lifted over this area and to be striking the slightly rising ground on the southern half of the lake bed. Spiralling streamers of dust arose from south of the water body to the region of the sand dunes, where an opaque cloud rose to 8,500 feet in the space of 1 mile or less.

On the western side of the lake, the rising dust was carried northward in a gigantic eddy to the vicinity of Bartlett Point. There, the uppermost part of the dust cloud was swept to the south over the rising lower portions of the cloud. Figure 22 shows the situation. Dust was being transported through the gap at Haiwee, through lower Centennial Pass, over the Coso Mountains, through Carricut Valley and Etcheron Valley into the Panamint Valley, and thence to Trona in Searles Valley (Figure 1).

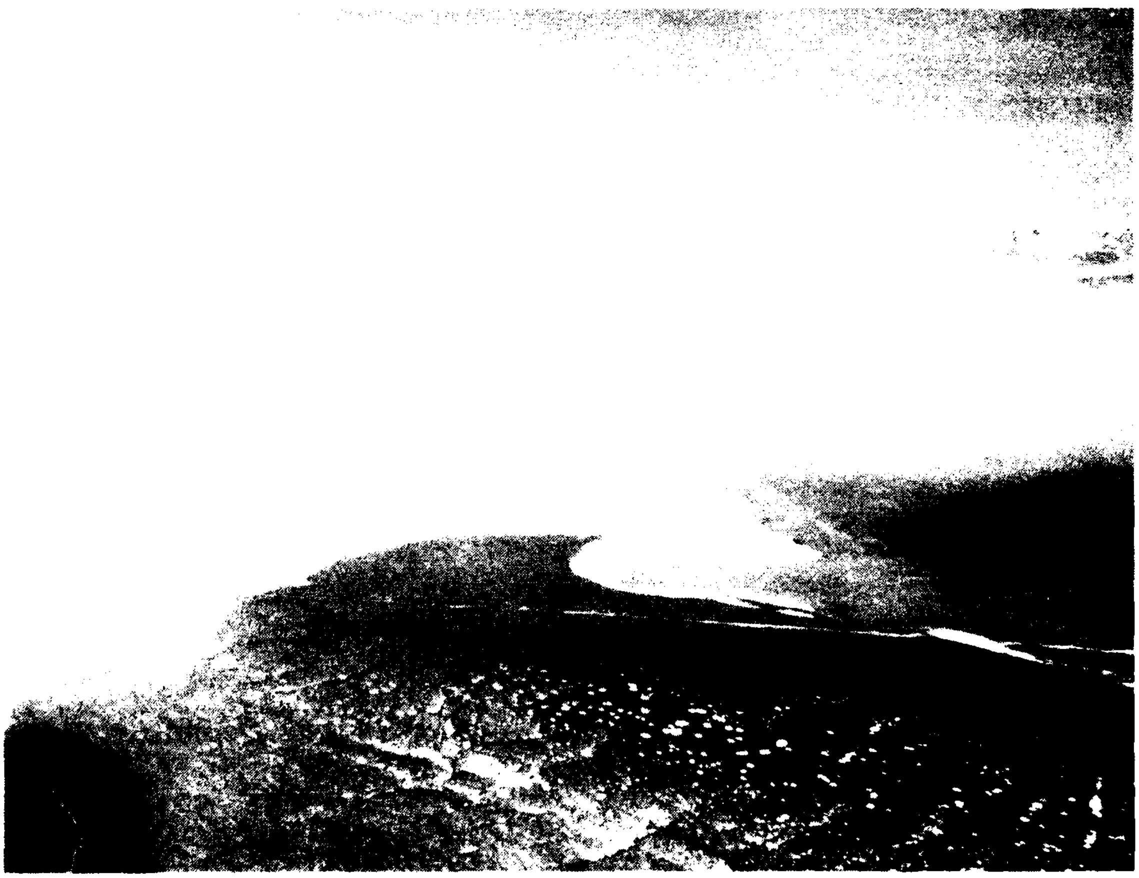


FIGURE 22. Owens Lake During Major Dust Storm.

Upon our return to Inyokern, the dust plume was concentrated on the western side of Indian Wells Valley; the eastern side had become remarkably clear. To the south, the jet of dust that passed over Inyokern spread out as the wind lost velocity in the expanses of the Indian Wells Valley and the Antelope Valley. The San Gabriel Mountains were still obscured.

By noon that day, the dust cleared in Indian Wells Valley, but between 1300 and 1500 the visibility decreased to 8 miles because of dust circling back from the southeast. At about 3,000 feet, a low-level counter circulation had been set up and dust- laden air was flowing northward into Searles Valley and thence through Burro Canyon to the north end of Indian Wells Valley. During the dust incursions, the visibility in different parts of Indian Wells Valley varies greatly. It is not uncommon to have a wall of dust in the western half of the valley, and but a minor amount in the eastern half.

DUST LOADING

On the day of the flight described above, a total suspended particulate load of 408.5 micrograms per cubic meter was measured over a 24-hour period at Trona by the San Bernardino County Air Pollution Control District. In the same 24-hour period, the Kern County Air Pollution Control District found 150 micrograms per cubic meter at the China Lake station. The dust storm at China Lake lasted from 3 to 4 hours, and the whole of the dust was deposited in that time span. Hence the loading at China Lake must have been 6 to 8 times these average values: close to 1,200 micrograms per cubic meter during the actual storm.

Twenty-four-hour samples yielding 350 micrograms per cubic meter are common. In almost every case, these are from dust storms that last only a few hours. The suspended particulate load often exceeds the alert level of 375 micrograms per cubic meter, established as the National Episode Criteria for particulate matter.

PARTICLE SIZE AND CONCENTRATION MEASUREMENTS

Size distributions of the dust particles were measured at China Lake by a Whitby Electrical Aerosol Analyzer and a Royco Optical Particle Counter (see Whitby, Husar, and Liu 1973 and Zinky 1962). The electrical aerosol analyzer counts particles having diameters between 0.0075 and 0.6 microns. The optical particle counter serves between 0.3 and 10 microns.It is thus necessary to use both instruments. The juncture between their areas of effectiveness is at about 0.4 microns. The electrical analyzer yields counts that are too high and the optical counter yields counts that are too low over the size range betwen 0.3 and 0.6 microns (Cook and Kirker 1975 and Carroz et al. 1977). The transition points between observations made by the two instruments can be noted in Figure 23. Both instruments are calibrated with small, spherical, plastic particles that have different optical and electrical properties than the airborne clays and alkalis, which are of irregular shape. The assumption that the aerosol particles are spherical leads to uncertainty in determination of size distribution and mass loading. Table 1 shows the mass loading of the aerosols and the visibility during the dust storms originating from Owens Lake, as compared with observations made during a clear day in the Indian Wells Valley and a smoggy day in Los Angeles.

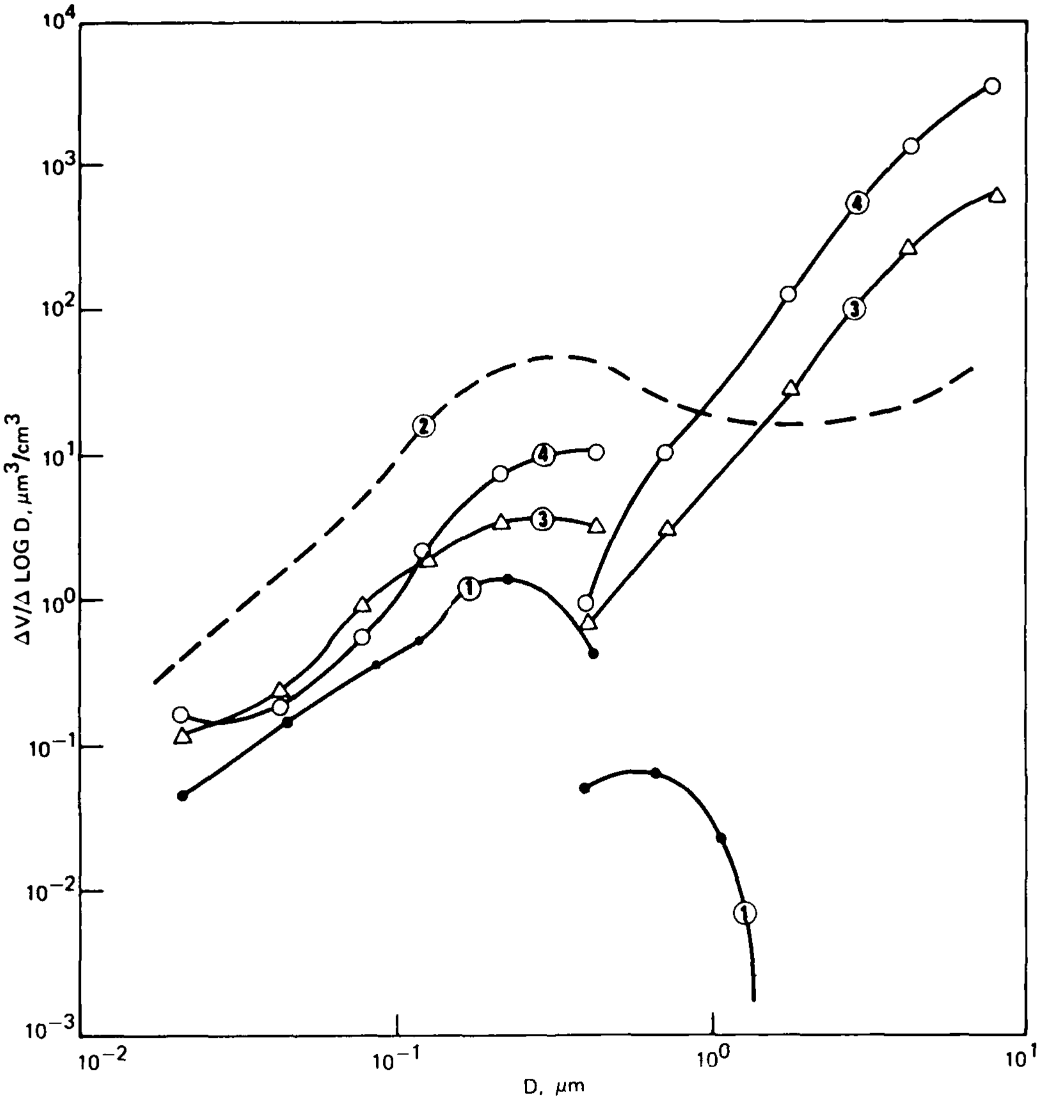


FIGURE 23. Plot of Volumetric Particle Distribution for Clear Air (1), Smog (2), 10-Mile Visibility (3), and 1-Mile Visibility (4).

TABLE 1. Mass Loading of Aerosol Particles in Clear Air, Smog, and Owens Valley Dust Storms.

Date	Time	Mass loading, $\mu g/m^3$	Visibility, miles	Condition
1/20/1978	1110	1.55	100+	Clear
8 and 9/1969	. . .	100	. . .	Smoggy
3/25/1976	1305	497	10	Dusty
4/16/1976	0920	2578	1	Dusty

We used Table 2 to prepare $\Delta V/\Delta \log D$ plots (Whitby et al. 1973). We assume that the particle count, ΔNi, measured for each size interval, Di to Di + 1, represents the number of particles having an equivalent diameter, D, equal to the square root of the product of the limiting diameters. The volume of an equivalent particle within each size interval is thus

$$\Delta Vi = (\pi/6)\ (DiD(i+1))3/2$$

Multiplying ΔVi by ΔNi gives the equivalent volume of the particles within one size interval.

The aggregate mass for each size interval is obtained by multiplying the volumes by a density appropriate to the size and the material: 2.0 for the dust, and 1.72 for the smog. Forming the sum of all sizes of particles we obtain the cumulative mass for the suspended material in micrograms per cubic meter.

Figure 23 shows the data plotted for clear air, for Los Angeles smog, and for visibilities of 1 and 10 miles in dust. The air entering Owens Valley on days when dust storms occur is remarkably clear and clean initially. For example, on 20 January 1978, with a gentle north wind, the total loading was 1.55 micrograms per cubic meter. PEDCO-Environmental Specialists, Inc., (1973) gives 25 to 30 micrograms per cubic meter as typical for this area. Visibility is usually in excess of 100 miles. During the dust storms, the number of particles is increased by orders of magnitude.

Figure 24 shows the visibility, V, plotted as a function of the suspended dust loading, Q, as determined at China Lake between 1975 and 1979. The limited data suggest a lineal trend on log-log paper. The geometric slope of near unity suggests that the equation developed by Middleton (1963) and by Noll et al. (1968)

$$\log V = Ca \log Q$$

TABLE 2. Cumulative Numbers of Suspended Particles per Cubic Centimeter of Air.[a]

Diameter, microns	Clear day (China Lake)[b]	Smog (Los Angeles)[c]	Dust (visibility 10 miles)[b]	Dust (visibility 7.5 miles[b]	Dust (visibility 5 miles)[b]	Dust (visibility 2.5 miles)[b]	Dust (visibility 1 mile)[b]
0.02	4.4×10^3	4.1×10^4	1.0×10^4	1.8×10^4	6.4×10^3	4.7×10^3	1.3×10^4
0.03	1.5×10^3	2.0×10^4	3.1×10^3	3.1×10^3	1.9×10^3	1.4×10^3	2.9×10^3
0.06	5.1×10^2	9.2×10^3	1.4×10^3	1.0×10^3	8.7×10^2	5.6×10^2	1.5×10^3
0.10	1.9×10^2	4.7×10^3	5.8×10^2	4.0×10^2	4.0×10^2	2.7×10^2	9.7×10^2
0.15	8.8×10^1	2.3×10^3	2.5×10^2	1.9×10^2	2.1×10^2	1.8×10^2	5.8×10^2
0.30	3.4×10^0	3.3×10^2	4.1×10^1	3.5×10^1	3.6×10^1	6.3×10^1	1.3×10^2
0.50	1.2×10^{-1}	5.0×10^1	1.2×10^1	7.6×10^0	1.2×10^1	2.7×10^1	5.1×10^1
0.80	1.1×10^{-2}	9.0×10^0	8.6×10^0	5.3×10^0	9.3×10^0	2.0×10^1	4.1×10^1
1.20	0	2.5×10^0	6.3×10^0	3.4×10^0	7.2×10^0	1.4×10^1	3.1×10^1
2.00	0	6.2×10^{-1}	4.2×10^0	2.0×10^0	4.8×10^0	8.0×10^0	2.0×10^1
4.00	0	1.2×10^{-1}	1.7×10^0	8.6×10^{-1}	1.9×10^0	3.5×10^0	8.4×10^0
6.00	0	3.5×10^{-2}	6.0×10^{-1}	2.3×10^{-1}	7.6×10^{-1}	1.1×10^0	3.3×10^0

[a] Cumulative number of particles with diameters greater than shown, but less than 10 microns.

[b] Measurements taken at China Lake, Earth and Planetary Sciences Laboratory: 2.5- and 7.5-miles visibility data taken on 20 May 1975, 5- and 10-mile on 25 March 1976, and 1-mile on 16 April 1976.

[c] Smog is summary for August and September 1969 by Whitby et al., 1972.

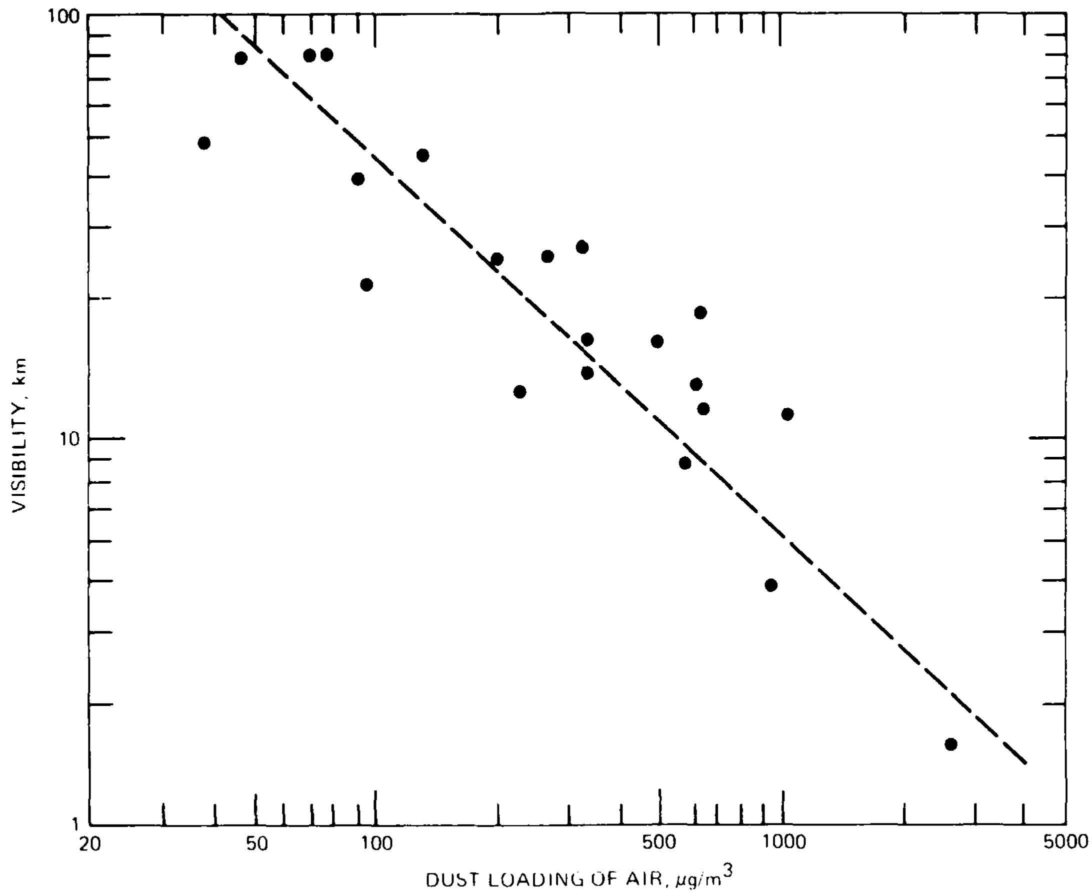


FIGURE 24. Visibility as a Function of Suspended Dust Loading.

where C and a are constants, is applicable to dust storms.The visibility depends on many factors, such as color of the dust, color of the background, phase angle of illumination, size and shape of the particles, and the complex dielectric constants of the dust; however, a simple relationship of this sort makes it possible to estimate suspended dust loading without recourse to an array of instruments. For example, on 26 March 1970, visibility was 0.25 miles for 3 hours and then averaged 2.5 miles for 3 more hours. Observations were only made for 16 hours on that day, and so for a 24-hour period, a minimum loading, as collected by a high-volume sampler, would have been more than 1,100 micrograms per cubic meter. The storm of 26 March 1975 would have yielded a minimum value of about 955 micrograms per cubic meter for 24 hours.

MASS OF MATERIAL INVOLVED IN A STORM

The amount of dust removed from the bed of Owens Lake by a storm can be estimated from the atmospheric loading. The mass of material, M, suspended over 1 square meter of the ground at a given time during a dust storm is given by

$$M = Q H \times 103$$

where M is the total suspended mass in micrograms, Q is the mass loading in micrograms per cubic meter, and H is the plume depth in kilometers, all values being averaged throughout the total column.

Assuming a loading of 1,000 micrograms per cubic meter and a plume height of 2 kilometers as being typical of the China Lake area during a severe storm, 2 tons of material are suspended per square kilometer. If this were an average value for the whole of the dust cloud from Owens Lake to the southern end of Antelope Valley, shown in Figure 25, the total suspended mass at the time of the photograph would be about 80,000 metric tons.

The flux of material from Owens Lake in one storm is many times this amount. The active surface of the lake is about 280 square kilometers. Assuming a density of 2 grams per cubic centimeter for the dust, a layer only 150 microns thick could produce the dust cloud that extends over the entire affected area. A wind of 25 meters per second could replenish the entire cloud every 3 hours. Thus about 7 tons of material would be removed each second. Sustained for 24 hours, such a wind would erode 0.12 centimeters of sediment, a thickness small compared to that of the dessication crust that overlies the lake bed.

FIGURE 25. Satellite Photograph of Dust Cloud Extending from Owens Lake to Southern End of Antelope Valley.

CHEMICAL COMPOSITION OF THE DUST

On 26 March 1975 a Lundgren Impactor was operated for 12 hours to obtain dust samples. These samples were analyzed by X-ray activation, and thus the clays and other rock particles were analyzed along with the alkalis. The average compositions for all particle sizes are given in Table 3. The main constituents are sodium, aluminum, silicon, sulphur, chlorine, potassium, calcium, and iron, as well as trace amounts of titanium, manganese, copper, zinc, and chromium. Although the X-ray activation techniques did not report the presence of sulfate or carbonate radicals, these are important constituents of the dust. The chemistry of the dust varies with the season of the year. It is to be expected that the earliest dust storms of the season would contain more alkalis than later storms. The color varies, ranging from ash-white to dove-gray to dark gray as the season progresses. Samples of dust furnished by the Great Basin Air Pollution Control District in 1985 were analyzed by ion chromatography. The analyses appear in Table 4. A study of the aerosols in Owens Valley was published by Barone, Kusko, Ashbaugh, and Cahill (1979).

TABLE 3. Average Elemental Composition of Dust for the Time Period 0800-2000 PST, 26 March 1975.

Element	$\mu g/m^3$	$\mu mol/m^3$
Sodium	224.7	9.774
Aluminum	63.8	2.365
Silicon	145.9	5.194
Sulfur	37.6	1.173
Chlorine	38.4	1.083
Potassium	29.7	0.760
Calcium	33.9	0.843
Iron	39.0	0.698
Magnesium	3.0	0.125
Titanium	3.4	0.071
Manganese	1.05	0.019
Copper	0.01	0.0002
Zinc	0.003	0.00005
Chromium	0.003	0.00006
Total	620.500	22.10500

TABLE 4. Percentage by Weight of Components of Owens Lake Dust Samples.

Date sample taken	Concentration, $\mu g/m^3$	Soluble, %	Na, %	K, %	Cl, %	NO_3, %	SO_4, %	CO_3, %
2/23/1985	207.69	15.60	31.40	1.41	8.65	2.46	9.57	46.48
3/ 3/1985	7627.9	4.16	39.14	0.76	7.74	0.14	14.87	37.35
3/ 3/1985	552.19	46.26	33.83	0.71	4.73	0.28	16.90	43.57
3/27/1985	989.03	16.04	31.40	0.85	6.91	0.23	20.60	40.02
3/29/1985	2059.55	10.96	45.00	1.23	11.70	0.05	13.33	28.69
4/26/1985	797.05	5.14	43.05	1.39	10.61	2.01	20.05	22.89
4/26/1985	371.82	66.90	32.26	0.85	6.23	0.79	12.45	47.42
4/26/1985	284.94	65.73	56.33	0.94	11.26	1.44	10.00	20.03
Mean weight, %			39.96	1.01	8.45	0.98	14.80	43.80
Mean mole, %			62.65	0.95	8.55	0.58	5.67	21.63
Standard deviation, mole, %			7.52	0.24	1.88	0.52	1.74	7.98

NOTE: Analysis by ion chromatography; HCO_3 and CO_3 are determined together. Samples courtesy of Great Basin Air Pollution Control District.

EFFECTS OF THE DUST

The airborne particles from Owens Valley storms are smaller than those from desert sand storms. The dust particles are nonabrasive and produce no sound on impact. The particles are electrically charged, cause radio static, and stick to windshields of automobiles and aircraft. Suspended wires develop a high charge that makes it dangerous to handle ordnance items during these episodes.

Dr. Bruce Chandler, M.D., F.C.C.P.; Dr. Robert Gilmer, M.D., F.C.C.P.; and Dr. Jack Schraeder, M.D., F.A.C.C. (personal communications) state that medical problems are aggravated by the dust. Patients at the Ridgecrest medical complex who suffer from emphysema, asthma, and chronic bronchitis are subject to increased morbidity. Hospitalization of these patients with bronchial spasm and related pulmonary problems increases during dust episodes. The populace complains of coughing, sneezing, and irritation of the eyes. Psychological problems emerge as some people become apprehensive because of difficulty in breathing. People become annoyed and anxious. Cats behave aberrantly. Dust enters buildings through cracks and crevices and covers exposed items.

Table 5 shows the mass of the particulate material deposited in the tracheobronchial region and in the pulmonary tract. The values are based on dust storm measurements from Table 2 and on average deposition fractions presented by the Task Group on Lung Dynamics (1966) and Stahlhofen, Gebhardt, and Heyder (1980). About 1/4 of the particulate material is clay; it is usually difficult to inhale clay, but the dust storms present an abundance of well-separated clay particles along with those of several alkalis. The physiologic effects of inhaling clay particles are not well studied.

TABLE 5. Material Deposited in the Tracheobronchial Region (TB) and in the Lungs (P).

	Tidal volume,[a] nasal breathing,[b] cc				Tidal volume, mouth breathing,[c] cc			
	750		1450		1000		1500	
	TB	P	TB	P	TB	P	TB	P
Micrograms of Aerosol Deposited Per Cubic Meter of Air Inhaled								
Clear day	0.03	0.37	0.03	0.47	0.03	0.43	0.03	0.46
Smog	3.40	20.00	2.50	20.00	7.20	29.00	6.70	24.00
10 mile visibility	18.00	28.00	8.50	15.00	92.00	86.00	78.00	43.00
1 mile visibility	89.00	132.00	41.00	68.00	483.00	412.00	406.00	203.00
Milligrams of Aerosol Deposited in 24 Hours								
Clear day	0.00	0.01	0.00	0.02	0.00	0.01	0.00	0.02
Smog	0.06	0.32	0.08	0.63	0.16	0.62	0.22	0.78
10 mile visibility	0.30	0.46	0.27	0.47	1.99	1.85	2.53	1.38
1 mile visibility	1.44	2.14	1.28	2.12	10.40	8.90	13.20	6.58

[a] Tidal volume = amount of air inhaled per breath.
[b] Average deposit fractions from Task Group and Lung Dynamics.
[c] Averaged deposit fractions from Stahlhofem, Gebhardt, and Heyder.

In the Sahara Desert, studies of the ecological effects of sand and dust storms indicate that there may be a significant health hazard depending on the type of dust. Lundholm (1977, p. 67), states that one might expect a very unhealthy dust coming from the numerous salt pans. Although little is known about the health effects of the dust, a report cited by Lundholm states that the Kalahari area of Botswana, which is very overgrazed in parts, has the highest death rate from lung diseases in the world.

PROVENANCE OF THE DUST

Visits to Owens Valley during windy conditions reveal that dust arises from the following places. The locales are listed in order from the ones that contribute the most dust to the one that contributes the least.

1. The southern half of the Owens Lake playa, usually beginning about a mile from any water body present.

2. The rest of the playa when not covered by water, including the northern portion (Figure 26).

FIGURE 26. Dust Storm (View from Northeast Side of Owens Lake).

3. The area immediately north of Tinnemaha Reservoir. This situation has been noted only when the water in Tinnemaha is low.

4. The valley floor between Independence and Owens Lake, for a short distance on either side of the river bed. This happens after a protracted dry spell.

5. The north and south shorelines. Sand, with but little dust, blows across the lakebed from these shorelines and forms sand dunes to the north-northeast and south of the lake. The dunes on the north side are being deflated, and those on the south side are accumulating a mile or two to the south of the lake; the area between is being deflated. The sand does not travel very far and ultimately is deposited in dunes. Some dunes form where updrafts tend to occur on the lake bed.

Areas near springs, which have been flushed clear of alkalis and have colonies of sacaton and other halophytic vegetation growing on them, do not produce dust. The boron content of the lake surface precludes the natural growth of vegetation thereon; but, where it has been flushed away, halophytic grasses and other vegetation seem to thrive. Figure 27 shows the area around an artesian well in wintertime, with a thick growth of alkaline crust over and around the grasses. Figure 28 shows the same area in summer with a verdant growth of grasses.

FIGURE 27. Area Around an Artesian Well in Winter.

FIGURE 2[illegible]

[illegible]

W[illegible]dstorms that [illegible] One typ[illegible] [illegible] episode occurs with s[illegible] across the Sierra and give rise to clouds of dust, as shown in Figure 2[illegible] [illegible] Walker Valley and Owens Valley, dust storms and sandstorms develop from th[illegible] when a rotor touches the ground, often lofting pea-size gravel into the air. [illegible] from the Sierra is heated by compression during descent and is then [illegible] against the [illegible] to the east. The photograph shows [illegible] in areas where soil has been disturbed. Desert sand is often [illegible] removal of smaller particles near the surface.

The situation that [illegible] a northerly wind comes through Owens Valley. The [illegible] that [illegible] on 25 [illegible] 27 March 1975 is summarized in Fig[illegible] storms [illegible] this one is typical of those that produ[illegible] storms. The sequence is as follows:

1. Prior to the Storm. [illegible] A low-pressure trough [illegible] polar air [illegible] with cyclogenesis.

2. Onset of the Storm. The [illegible] at all levels shift to the north-northw[illegible] Surface winds often exceed 40 knots. [illegible]

trough passes to the east over Owens Valley. Arctic air is advected at all levels up to a few hundred millibars. The lapse rate is extremely stable; the air is dry and cold. The air drops from about 9,000 feet in the Mono Lake region to about 2,500 feet in the Indian Wells Valley. The already dry air is thus heated by compression. The relative humidity often drops to less than 10%.

3. Visibility Reduction. Minimum visibility occurs some hours after the onset of the storm. Strong winds from the north-northwest continue as the visibility decreases. Winds subside at the surface before clearing begins.

4. Clearing. Clearing occurs when the winds at the ground weaken and/or change direction so that they are no longer aligned with Owens Valley. The period of clearing may be prolonged, with remissions and exacerbations of the storm. Dust is deposited on bushes, and any winds that blow within a week after a major storm produce minor, secondary, local episodes from this source.

Within Owens Valley, wind from any direction in excess of 15 knots causes lifting of dust from the lake bed. To describe all the meteorological situations that will produce this gamut of results is impossible.

FIGURE 29. Dust Clouds Raised by Westerly Winds Blowing Across the Sierra (View Looking South).

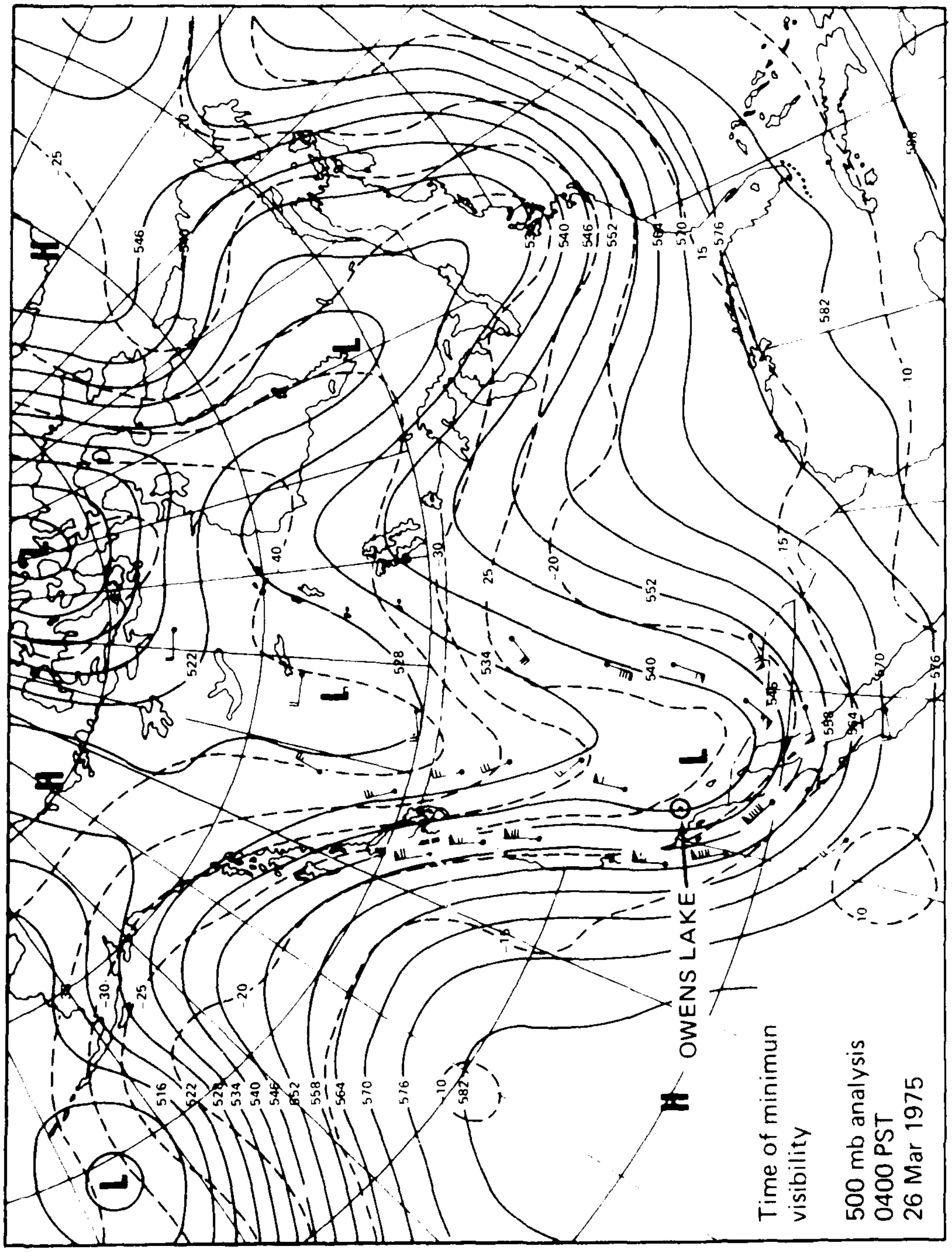


FIGURE 30. Synoptic Situation During Time of Minimum Visibility in 26 March 1975 Dust Storm.

CONDITIONS ON THE PLAYA SURFACE

If dust is to be produced from the playa, the surface material must be such that it can be picked up by the wind or be amenable to being dislodged by a secondary agent. We will now describe the playa under different conditions of weather, season, and water supply.

The playa is fairly flat and uniform in appearance, but conditions on the surface vary widely. Owens River has created a delta that overlies and interfingers with the clays of the lake bed. Water collects in the western sump and to a lesser extent in low places on the eastern side. Numerous springs have locally modified the surface, washing away saline water and the alkali crust that often develops. Abandoned artesian wells locally flood their surroundings, giving rise to lush growths of grasses.

Abandoned evaporators, pipe lines, tracks, and roads are spread over the entire lake. Refuse from mining operations is being piled in one locality on the eastern shore. Large deposits of evaporites are located in the sump. The lake is fringed with shorelines and beach bars developed during the high stand of 1913. Mud volcanoes, developed in the vicinity of fault zones during past earthquakes, are arranged in lines on the playa, indicating the likely course of recently active faults. Large cracks cross the surface.

Some secondary grabens lie on the valley floor to the north of the lake bed. The surface of the lake bed is fractured into huge polygons that are visible when the playa is dry. To some extent, the distribution of the materials on the surface is changed by wave action during periods of flooding. Wind redistributes sand, making and destroying small dunes and removing large quantities of alkali and clay.

LAKE WATER

Numerous analyses of the water in Owens Lake have been made since the first one was conducted by a Professor Phillips of England in January 1866 (Phillips 1877). This and subsequent analyses are cited by Willis Lee (1906), Gale (1914), and Clarke (1924). These results, as well as a few more recent ones, are given in Table 6. On the basis of these analyses, the total solute load of Owens Lake is estimated to be 160,000,000 tons of anhydrous salts (Gale 1914). This treasure trove of sodium products works out to 67,000,000 tons of sodium chloride; 63,000,000 tons of sodium carbonate; 23,000,000 tons of sodium sulfate; and 7,400,000 tons of potassium, boron, iron, aluminum, lithium, etc.

These substances, as strange a cast of characters as ever appeared in an ionic soap opera, readily change their chemical and physical properties, forming a wide variety of complexes, depending upon conditions to which the substances are submitted. When concentrated, they precipitate a minerologist's delight of evaporite minerals to be identified and named. The worst part is that they do not stay fixed; many are hydrated, and these change dramatically with variations in temperature, pressure, humidity, and atmospheric carbon-dioxide content.

These compounds change composition while being sampled, transported, and tested. The lake brine dissolves glassware rapidly enough to change the apparent concentration of the silicate ion in a short time. Inclusion of suspended particles of silt in the sample can easily lead

TABLE 6. Analyses of Waters From Owens Lake and Owens River.

Date of analysis	Na, %	K, %	SiO_2, %	Cl, %	SO_4, %	CO_3, %	HCO_3, %	TDS %	Density	Reference
1/–/1866	41.90	3.30	0.90	24.60	12.50	16.70	. . .	10.36	1.067	Phillips, 1877
1/–/1866	41.90	3.30	0.90	24.60	12.50	16.70	. . .	10.36	1.067	Phillips, 1877
10/–/1876	35.58	4.55	0.27	22.28	15.46	21.86	. . .	6.56	1.051	Loew, 1876, p. 190
3/–/1882	40.63	W/Na	. . .	25.80	9.97	23.60	. . .	6.88	1.063	Lunge, 1890
9/–/1886	37.83	2.18	0.29	25.76	9.95	23.51	. . .	7.27	1.062	Chatard, 1889
–/1902	42.79	2.20	0.29	25.75	10.00	18.34	. . .	. . .	. . .	Anon., cited by Gale, 1914
8/–/1905	38.09	1.62	0.14	24.82	9.93	24.55	. . .	21.37	1.195	Stone et al., cited by Lee, 1906, p. 22
5/–/1912	. . .	. . .	. . .	. . .	. . .	. . .	. . .	9.59	1.085	Bailey, 1902, p. 95
10/–/1912	38.07	2.10	0.21	25.56	9.96	22.18	. . .	10.95	1.098	Hicks, cited in Gale, 1914, p. 258
2/–/1914	37.83	2.09	0.20	25.40	9.89	22.70	. . .	11.88	1.098	Hicks, cited by Clark, 1924
2/–/1970	37.81	0.73	0.16	18.65	9.18	21.29	11.82	13.62	1.1	Friedman et al., 1976, pp. 405-406
8/–/1970	38.14	0.82	0.15	19.69	9.74	26.63	4.43	25.04	1.18	Friedman et al., 1976, pp. 405-406
9/16/1971	38.44	0.85	0.16	20.30	10.18	23.90	5.83	29.66	1.2	Friedman et al.
1/19/1971	38.57	1.59	0.10	37.20	5.34	13.30	3.32	23.98	1.16	Friedman et al.
1/19/1971	38.90	1.60	0.11	37.28	5.29	13.15	3.12	25.32	1.17	Friedman et al.
4/13/1971	38.71	1.27	0.12	29.94	10.22	18.27	0.94	38.75	1.26	Friedman et al.
7/7/1971	38.22	1.77	0.24	28.77	8.29	22.07	W/CO_3	45.00	1.3	Friedman et al.
8/20/1971	38.06	2.74	0.24	24.03	5.65	28.08	W/CO_3	47.03	1.31	Friedman et al.
8/6/1985	39.70	2.85	0.28	33.80	9.17	13.29	. . .	34.90	. . .	Gaines, 1985
Mean, %	38.78	2.02	0.24	26.45	9.45	18.44	4.91	24.60	1.15	
Composition of Water From Owens River										
–/–/1908	19.83	W/Na	12.40	9.49	15.53	29.84	. . .	0.34	. . .	Clark, 1924, 36 ten-day samples during year[a]
6/7/1965	11.76	1.54	8.14	6.33	7.69	4.52	58.82	0.02	. . .	Clark, 1924, taken at inlet to Haiwee Reservoir

NOTE: In some early samples, potassium is included with sodium, bicarbonate with carbonate.
In lake water, borate ion averages about 0.62%; lithium, calcium, magnesium, iron, and aluminum average 0.01 to 0.04%, when determined.

[a] Sample taken at Charley's Butte.

to an increase in the silica content without representing dissolved silica in the original sample. This may have happened with the samples of river water cited in our Table 6. The brine can also take up carbon dioxide from the air in sufficient quantities to change the bicarbonate ion concentration during storage, unless the sample is very carefully sealed. Trona can be precipitated during periods of high temperature, thus removing a complex of sodium carbonate, sodium bicarbonate, and water from solution. Mirabilite and natron form during cold weather, but will either melt or dehydrate as you watch them. The laboratory results vary a good deal because of the difficulties involved in transport, storage, and analysis. In former days, the bicarbonate ion was determined along with the carbonate ion, as probably was the borate ion. Lithium and potassium were often analysed as sodium. Determination of the bicarbonate ion in the presence of much carbonate is still difficult.

HYDROBIOLOGY

The water in Mono Lake is not colored, but water in Owens Lake has a red tint, described by explorers in the 1800s. Chatard (1890, p. 95) discusses the coloration. He cites Payen who contended that decomposing *Artemia* caused the red color. Although this observation has been widely quoted, we do not think that this is the reason for the color. Brine algae in saline solutions include *Dunaliela salina* and *D. viridis*. *Dunaliela salina* colors brine red. A few types of bacteria that exist in these environments also give brine a red color. *Halobacterium* and *Halococcus* (chemo-organotrophic halophilic bacteria) are red due to carotenoids in the cells (Larsen 1980, p. 25). Jannasch (as cited by Larsen 1980) found that the red, phototrophic sulfur bacteria *Thiorhodaceae* dominate Wadi Natrun, a carbonate playa in Egypt from whose name, by mispronunciation, the word Trona arose. Other sulphur metabolizing bacteria are *Chromatium* and *Ectothiorhodospira* (Larsen 1980, p. 30).

The red color of the microorganisms may reduce the effects of sunlight on the biota and raise the water temperature, giving the microbes a longer growing season (Dundas and Larsen, as cited by Larsen 1980). Richard Tew, a resident of Keeler, has made a series of studies on the microorganisms in the lake (Tew 1966 and 1980).Bacteria that metabolize sulphur, given enough time, are capable of changing the chemistry of the lake waters. The algal components and the plant flagellates are also quite capable of changing the carbon dioxide content of the lake waters.

LAKEBEDS

The floor of Owens Lake is composed mainly of lacustrian clays, covered in places by a sand layer of variable thickness. The uniformity of the surface is broken by evaporators on the eastern and western sides and by the delta of the Owens river on the north. The delta consists of coarser debris deposited onto the lake while the river was flowing. Since the river dried up, the only material brought in has been fairly coarse debris swept along during periods of heavy rain, or when excess water was dumped into the lake.

The lacustrian clays are fine grained, highly cohesive, and run the spectrum of colors from greenish gray to black. Droste (1961) identifies the clays as illite and montmorillonite and lesser amounts of chlorite and kaolinite. Some of the clays near the surface are mixed with aeolian sands. The dry surface of the playa is covered with an alkaline crust. When the lake surface is dry, hot, and has not been recently wetted, the crust is quite hard and easily supports the

weight of people and vehicles. The crust is arched up, out of contact with the underlying clays, except for occasional points that support the mass. Once the crust is wet and the temperature is low, the crust is puffy, soft, and friable. While the crust is wet it can not support its own weight and falls on the clays beneath. The reasons for these changes will be discussed later, along with the chemistry of the crust.

The moisture content of the clay increases with depth, unless rain has recently fallen, in which case the surface may be quite wet. The uppermost clay is usually dry, but at a depth of a few inches it becomes damp and at a depth of about 2 feet it is wet and plastic (see Table 7). On the surface itself, the edges of the cracks, which form the sides of polygons several feet to 10 or more feet in diameter, are upturned, with a generous growth of saline crust on the edges (Figure 31). In cross section, these polygonal cracks descend into the clay as distinct fractures that reach the plastic damp material beneath. Figure 32 shows the effects of water being piped into the clay beneath by means of the fractures.

The clay in the dried zone is friable, and the pieces are well separated. To a depth of a few inches in late winter to 2 or 3 feet in early autumn, the clay is broken into pieces less than an inch in diameter. The sizes of the pieces and of the fractures increase with depth. At a depth of about 2 feet, the pieces between fractures are up to several inches in diameter. The fractures do not extend into the damp, plastic clay; but as the clay dries further, the fractures continue to propagate downward (Figure 33).

When the playa has been dry for 2 or 3 months, the upper 4 to 5 inches of crust crumbles and dissaggregates into pieces a centimeter or less in diameter. This disturbance to the clay in the upper levels has been postulated to be chemical in nature, caused by the growth and destruction of crystals of the various saline materials. This may happen, and in fact in other playas we have seen small flecks of gypsum in the spaces between cracks. We feel, however, that this fracturing is brought about by drying of the expansive clays. The progressive deepening of the cracks over the space of a month or less in the "dry season" indicates that dessication is the primary mode of formation of this zone. The clay beneath the crumbled zone is often a dark black solanetz with fragments of leaves preserved therein. The organic material has apparently been reduced to carbon by action of the carbonate ion. The lack of such organic detritus in the upper disturbed region indicates that it has been aerated by virtue of its porosity, whereas the clay beneath the disturbed layer has not been so oxidized.

TABLE 7. Composition of Cores Taken at Owens Lake.

Date core taken	Site[a]	Depth, ft	Na, %	K, %	SiO_2, %	Cl, %	SO_4, %	CO_3, %	HCO_3, %	B, %	Soluble,[b] %	Insoluble,[c] %	H_2O	Remarks
10/10/1985	SP	0.5	4.4	0.3	...	3.5	2.4	1.07	bt[d]	0.1	11.79	88.21	36	Hand dug
10/10/1985	SP	1.0	17.6	2.5	...	2.3	6.3	16.3	bt	0.32	45.2	54.58	36	Hand dug
11/15/1985	SP	1.0	15.6	0.34	...	22.0	9.7	2.85	bt	...	50.49	49.51	40	Hand dug
11/15/1985	SP	2.0	3.03	0.23	0.16	5.6	9.8	0.98	1.22	0.06	21.27	78.73	41	Core
11/15/1985	SP	4.0	2.44	0.16	0.14	3.1	1.7	0.71	bt	0.04	8.34	91.6	41	Core
10/10/1985	WC	2.5	3.1	0.21	...	1.7	2.5	0.98	bt	0.06	8.57	91.43	41	Core

NOTE: The water content of the clays was determined separately from the chemistry.
[a] SP indicates old sulphate plant in center of playa; WC is the Westec site on the west side of the playa.
[b] Indicates all material soluble in water.
[c] Indicates material not soluble in water, but includes water of hydration and water in clays.
[d] bt indicates below threshold of detection.

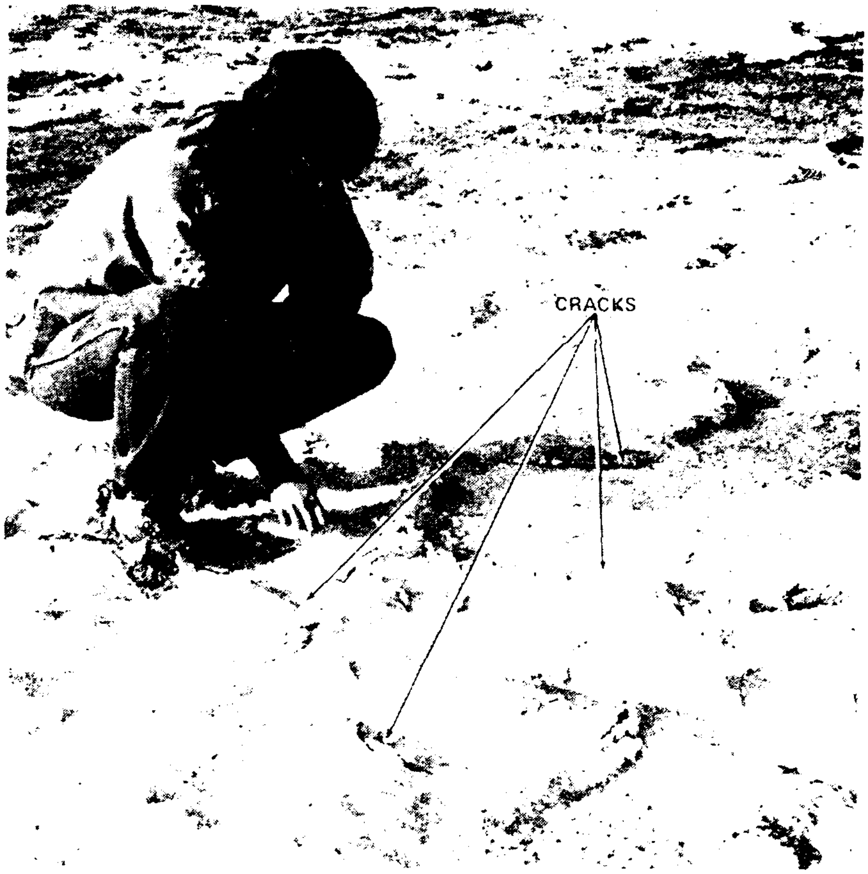


FIGURE 31. Cracks in the Playa Surface.

In the vicinity of clastic dikes and fractures, the bluish black color is absent, and the clay is the usual gray or buff for distances of several centimeters from the fractures. Following rain, snow, or other wetting, the hard crust of summer collapses and falls upon the disturbed layer, wetting it. This disturbed layer then swells, recompacts, and improves the hydrologic continuity with the damp clays beneath. The result is a seasonal opening and closing of the cracks; the resulting aeration destroys the organic material that ordinarily colors the clays black (Figure 33).

The clays are not very permeable. A hole dug deeper than the level of an adjoining water body will not fill with water for days on end. The fine particle size of the clays results in a very considerable tendency toward capillary uplift of water from below.

On the other hand, in localities within a mile or so of the water body, where coarse sand overlies the clays to a depth of a few feet, the tendency toward capillarity is greatly reduced because of the larger particle sizes of the sand and the much greater void spaces. Here, the alkaline crust may be almost entirely absent, even though it may be well developed a few feet away in any direction where clay is present at the surface. Instead, areas with deep sand remain loose and free of salts to a depth of a foot or so, depending upon the groundwater level. Immediately below this loose material, right on top of the water, the sand is well cemented by

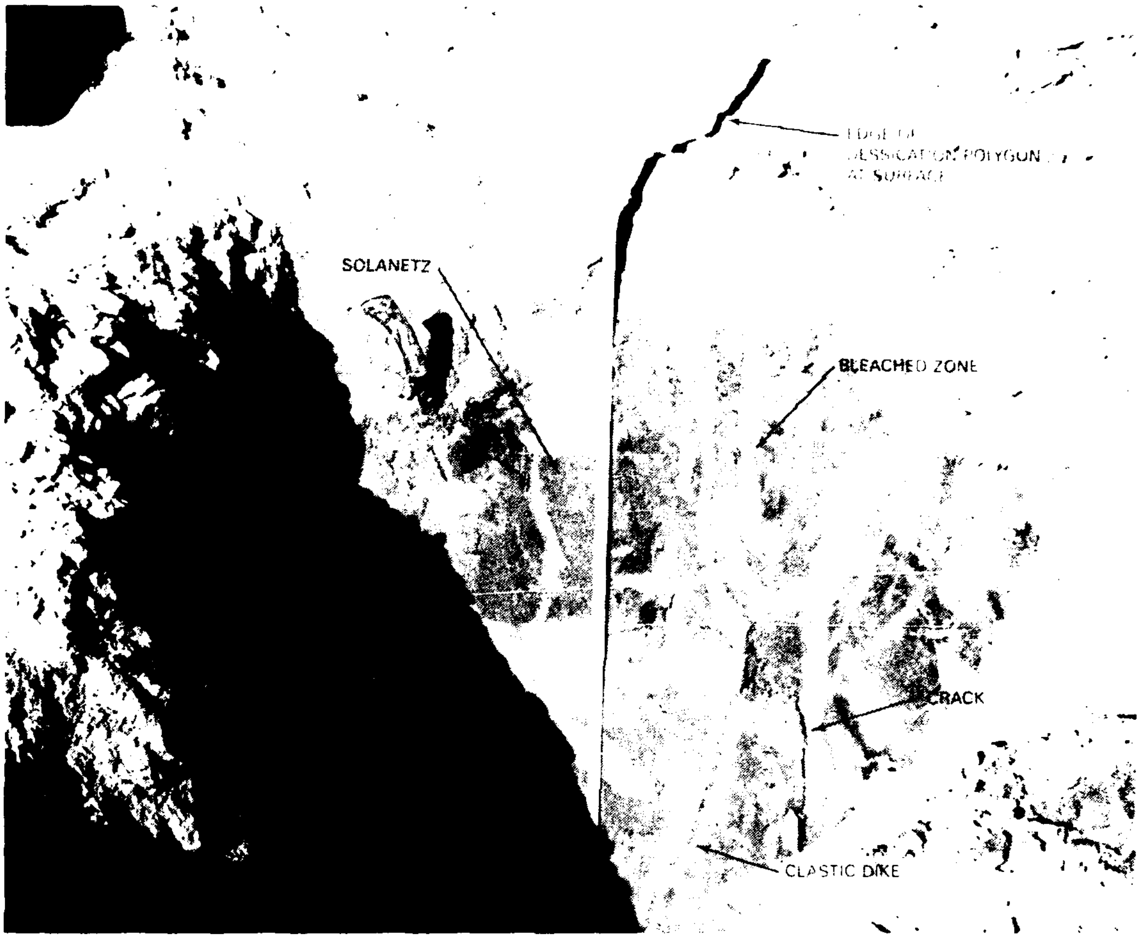


FIGURE 33. Cracks With Clastic Dikes and Solanetz.

a solid, hard mass of crystalline salts. Such salts are rarely, if ever, found within the clay mass except in the westernmost sump, where saturated solutions remain for years at a time on top of the clays, and other clay, deposited on top of a layer of evaporites, may protect the evaporites from solution.

Ordinarily, as noted by Foshag (1926, p. 57-58), most of the salines are concentrated at or just below the surface, and the clay beneath the alkaline crust in a playa is not saturated with salts. At a depth of a foot or so, the solution is dilute. On Owens Lake, however, when the level of the brine in the water body has been extraordinarily high because of partial refilling of the lake and redistribution of some of the brine, the rising groundwater near the water body is more concentrated and will remain so until the alkali has been retransported to the surface. Strong winds blow the brine about on the flatter parts of the playa surface and so spread it laterally from the free water. Core samples from the Westec area and from the vicinity of the

Old Sulfate Plant (see Figure 9) were analyzed for solutes and for water content. The results appear in Table 7. The clays contain up to 48% water by weight; the total solute varies from 8% to 50% depending upon depth and upon the state of recent flooding of the playa.

Unless the area has been subjected to an increase in brine by flooding of the lake, the salines present at the surface are probably derived from the vertical transport of groundwater by capillarity. The capillarity works best when the clay is not disrupted by fracturing or is not mixed with sand. When it is, the water reaches the surface primarily by vapor-phase transfer through the cracks, condensing in the upper portions as the surface cools at night. When the surface is damp, the capillary conductivity is greatly enhanced because the particles are once again in intimate contact.When the saline crust wholly or partially dissolves in the first few centimeters of the surface sands and clays, osmosis comes into play and migration of more dilute water from beneath is hastened. Osmosis and capillarity then work together. A combination of these effects causes the alkaline crust to grow faster in winter than in summer. On this basis, the assumption that evaporation rate from the surface of a clay playa depends primarily on temperature is in question; more groundwater may be evaporated in the winter because more of it is nearer the surface and is less protected from what heat there may be.

Upon dampening of the surface in hot weather, the superficial material dissolves. This process leaves an area of high saturation near the surface; however, with respect to the clays at a depth of only a few centimeters, the solution is supersaturated because the clays are cooler. The ions of the solute migrate downward into the cooler region below, where temperatures of only 15°C are common. There the solution is supersatured and precipitation of the salines results just below the surface. Thus when the temperature is high, the Soret effect becomes noticeable.

Following a light rain in July 1985, when the soil temperature at the surface sometimes exceeded 65°C in the early afternoon on windless days, new crystal growth on the underside of the crust was quite apparent. This growth consisted of a centimeter or more of fine transparent crystals with hair-like apophyses that descended into the clays beneath. Where the crust was arched up, the slender crystals extended down into the open spaces below.

Without rain to dampen the surface, the effect is not noticeable, except near the brine pool where the water table is so high that the soil remains permanently moist. There a thin layer of crystaline material develops beneath a layer of damp clay only a few millimeters thick. The two layers are separated by a gelatinous solution, possibly containing dissolved silica. A silica gel has been reported in hydrothermal waters in Lake Magadi, Kenya, at temperatures between 67 and 82°C and pH about 9 (Eugster and Jones 1968, p. 160).The temperature in the first centimeter may reach 60 to 65°C, but the temperature of the water beneath may only be 15°C or less. At the high surface temperatures, the hydrated versions of sodium sulfate and carbonate break down to the monohydrates and anhydrous forms, with release of water and adsorption of heat. Thus the precipitated crystal body can act as a gigantic heat sink in the permanently damp, concentrated brine.

CHEMISTRY OF THE CRUST

The concentration of the various ions in the crust varies from place to place on the surface of the lake bed. Near the water body, the composition is probably identical with that of the lake brine in terms of the relative amounts of the various ions present. In places near flowing wells and springs, or where the salines are derived from rising groundwater, the composition is probably richer in chlorides and relatively impoverished with respect to sulfates and carbonates. A thick deposit of trona was removed from an area several hundred feet square on the south side of the road leading to the Lake Mineral workings. A new crust that contains almost pure sodium chloride has grown in this area.

We have conducted analyses of the crust at a few places. The results for the Westec site area and for the sulfate Plant area are given in Table 8 for various seasons of the year. The nature of the salts involved are such that small changes in relative humidity during storage and preparation for testing may result in changes in the composition because of the accumulation or loss of carbon dioxide and water from the air. We have taken pains to keep the samples well sealed and at reasonable temperature, but it is not possible to guarantee that no changes took place.

The analysis of dust from samples collected by the Great Basin Air Pollution Control District were presented in Table 4. The relative amounts of the various alkalis are about the same as those in the samples of the crust taken in the wintertime, except that the samples of the dust that we had were enriched with respect to sodium carbonate. Table 9 summarizes the analyses of the waters, cores and crusts; in the section on crusts, we did not include aberrant samples that were taken from places where some special activity had altered the chemical composition of the water or the playa. The analysis, by ion chromatography, interpreted carbonate and bicarbonate as one compound because in the process of determination, the carbonate changes to bicarbonate. The size of the samples did not permit a careful distinction between these phases. In the future it would be well to get larger samples and to sample each storm in turn throughout the season in order to distinguish between the bicarbonate and carbonate ions.

The primary active agents are sodium chloride, sodium carbonate, and sodium sulfate. Potassium and lithium compounds account for only a few percent of the material, and these compounds should not behave markedly differently from the sodium compounds. Little or no alkaline earth ions are present because they are rapidly precipitated by the carbonate and sulfate ions.

The composition of the alkali crust depends upon the degree of moisture present, the concentration of carbon dioxide in the water and air, and even more so upon the temperature. While sodium carbonate was being recovered commercially from the waters of the lake, the solutions were concentrated in evaporation pans on the edges of the lake. In summer, trona, a sodium sesquicarbonate-dihydrate, formed and was precipitated in the ponds. The trona thus recovered, called "summer soda," was heated to drive off the water and the excess carbon dioxide. The anhydrous or monohydrated sodium carbonate was shipped out. This process became obsolete when the lake water itself became so concentrated that the trona precipitated onto the lake bottom. Subsequently, the water was further concentrated and placed in large tanks where it was carbonated with carbon dioxide recovered from flue gases or produced from limestone and dolomite from nearby mines. Owens Lake was the main source of soda ash for the United States for many years, and much soda ash was shipped to China for the manufacture of fine porcelain.

TABLE 8. Analyses of Crust and Minerals From Owens Lake Playa.

Date sample taken	Site[a]	Na, %	K, %	SiO_2, %	Cl, %	SO_4, %	CO_3, %	HCO_3, %	B, %	Soluble, %	Insoluble, %	Remarks
8/6/1985-1	WC	16.10	0.97	. . .	6.10	5.50	5.03		bt[b]	33.70	53.40	Hard crust on sand.[c]
9/24/1985-1	WC	4.13	0.29	. . .	2.60	1.40	bt	bt	. . .	8.45	91.55	Hard crust with hairy crystals on underside.
9/24/1985-2	WC	18.36	0.60	0.36	24.00	10.20	3.60	bt	0.18	58.33	41.67	Hard crust with hairy crystals on underside.
9/24/1985-5	AW	32.90	. . .	. . .	0.97	64.50	bt	bt	. . .	98.41	1.59	Soft white crust in pond on eastern side.[d]
9/24/1985-7	SP	12.10	. . .	. . .	2.50	15.00	2.57	bt	. . .	32.20	67.00	Resistant crust.
9/24/1985-8	SP	37.12	. . .	. . .	53.20	0.70	8.60	bt	. . .	99.60	0.40	Blade like crystals growing on water, good cleavage.
10/10/1985-1	WC	25.60	0.66	. . .	0.36	9.50	12.90	bt	. . .	49.03	50.97	White, puffy, hard crust whith sand and clay.
10/10/1985-2	WC	16.70	0.70	. . .	1.70	2.80	5.30	bt	0.20	27.67	72.33	Same place as 9/24/1985-2[e]
10/10/1985-8	SP	10.50	0.37	. . .	11.00	20.60	3.15	bt	. .	35.14	64.86	Soft powdery crust on mine dump near eastern shore
10/10/1985-11	SP	13.90	0.06	0.13	0.66	20.30	1.31	bt	0.04	36.44	63.56	Crust from around artesian well *near* road to SP
11/15/1985-1	WC	9.60	0.51	0.30	6.00	4.60	4.50	bt	. . .	25.65	74.35	Crust wite, lumpy, and soft, same place as 10/10/1985-2.
11/15/1985-4	WC	9.70	0.69	. . .	8.00	4.40	2.68	bt	0.20	25.69	74.31	Moist ochric earth, below second crust about 4 inches deep.
1/15/1985-6	SP	9.49	. . .	. . .	2.10	1.30	3.66	bt	. . .	16.55	83.45	Soft top crust with some clay.
1/15/1985-7	SP	33.15	0.06	. . .	9.00	0.90	0.38	0.14	. . .	43.60	56.37	Clear crystals growing in old evaporation pond.

[a] SP indicates old sulphate plant in the center of the playa. WC indicates the Westec site on the west side of the playa; AW indicates an artesian well.

[b] Indicates below threshold of detection.

[c] Total solubles were 46.6% of sample. Probably contained water of hydration.

[d] Sample was anhydrous sodium sulphate, after repeated X-ray examination lines of Thenardite began to show.

[e] Crust much puffier, had hairy crystals growing down from underside into voids.

TABLE 9. Summary of Composition of Principal Components of Owens Lake Salines.

Sample from	Na, %	K, %	Cl, %	NO_3, %	SO_4, %	CO_3, %	HCO_3, %	SiO_2, %	Remarks
River water	22.73	. . .	10.88	. . .	17.80	34.21	. . .	14.21	Sample reported in Clark, 1924, adjusted to 100%.
Lake water	38.78	2.02	26.45	. . .	9.45	18.44	4.91	0.24	Mean of all values.
Clay cores	34.17	3.12	15.34	. . .	27.01	19.08	. . .	0.75	Mean of all values of soluble materials, adjusted to 100%.
Crust	37.64	1.90	21.69	. . .	23.21	14.58	. . .	0.98	Mean of values for undisturbed playa surface, adjusted to 100%.
Dust	39.92	1.01	8.45	0.98	14.80	24.80	. . .	. . .	Mean of all values of soluble materials, adjusted to 100%.

In the winter when the temperature drops, trona does not form; however, natron, a decahydrate of sodium cabonate (called "winter soda"), formed ice-like crystals in the evaporation ponds. These were recovered and exposed to the air, to which their water of hydration was lost. The resulting amorphous powder was then shipped as "soda ash," anhydrous sodium carbonate. Production by this process came to an end when the lake level fell below the point where it was profitable to pump the brine into the evaporators. Eventually, more profitable schemes involving the injection of carbon dioxide into the brine and careful recovery of the boron content were used. These too came to an end when readdition of water to the lake during good water years diluted the concentrated brine to the point where the newer plants could not handle it effectively, and some of the facilities were covered by water.

The process upon the surface of the playa reflects these reactions to a large degree. Figure 34 is a logic diagram that shows the reactions that occur on the lake surface as a function of temperature and humidity. This diagram is oversimplified to the extent that we have not considered the formation of complex minerals such as Brookite and the other rarer species. Various polyhydrates seem to be present at the lower temperatures. An economic lemma of Occam's Law entered here; having identified the process involved, we were forced to stop, leaving the elaboration of further detail to others. The minerals of greatest importance are called out in Table 10. It is not quite appropriate to regard them as minerals *sensu strictu* because some are amorphous. The crust, when damp, is more properly regarded as a collection of ions than a group of discrete compounds.

Of the minerals shown in Table 10, only halite, natron, thermonatrite, thenardite, mirabalite and trona play an important role in the development of the surface crust, although dihydrates and septahydrates are also present. Nacholite can not form under ordinary atmospheric conditions because of insufficient carbon dioxide or temperatures that are too low. The species involving calcium are not found in important quantities because the abundance of the carbonate ion causes precipitation of the alkaline earths. Burkeite is found in the crystal body that develops in the concentrated brine (Smith, Friedman, and McLaughlin 1986), but has not yet been identified on the surface of the playa. It has been reported from other playas (Jones 1962, p. 3569).

The right side of Figure 34 shows the summertime processes. Starting with clay that contains brine, one notes that if the temperature is greater than 17.9°C (Eugster and Smith

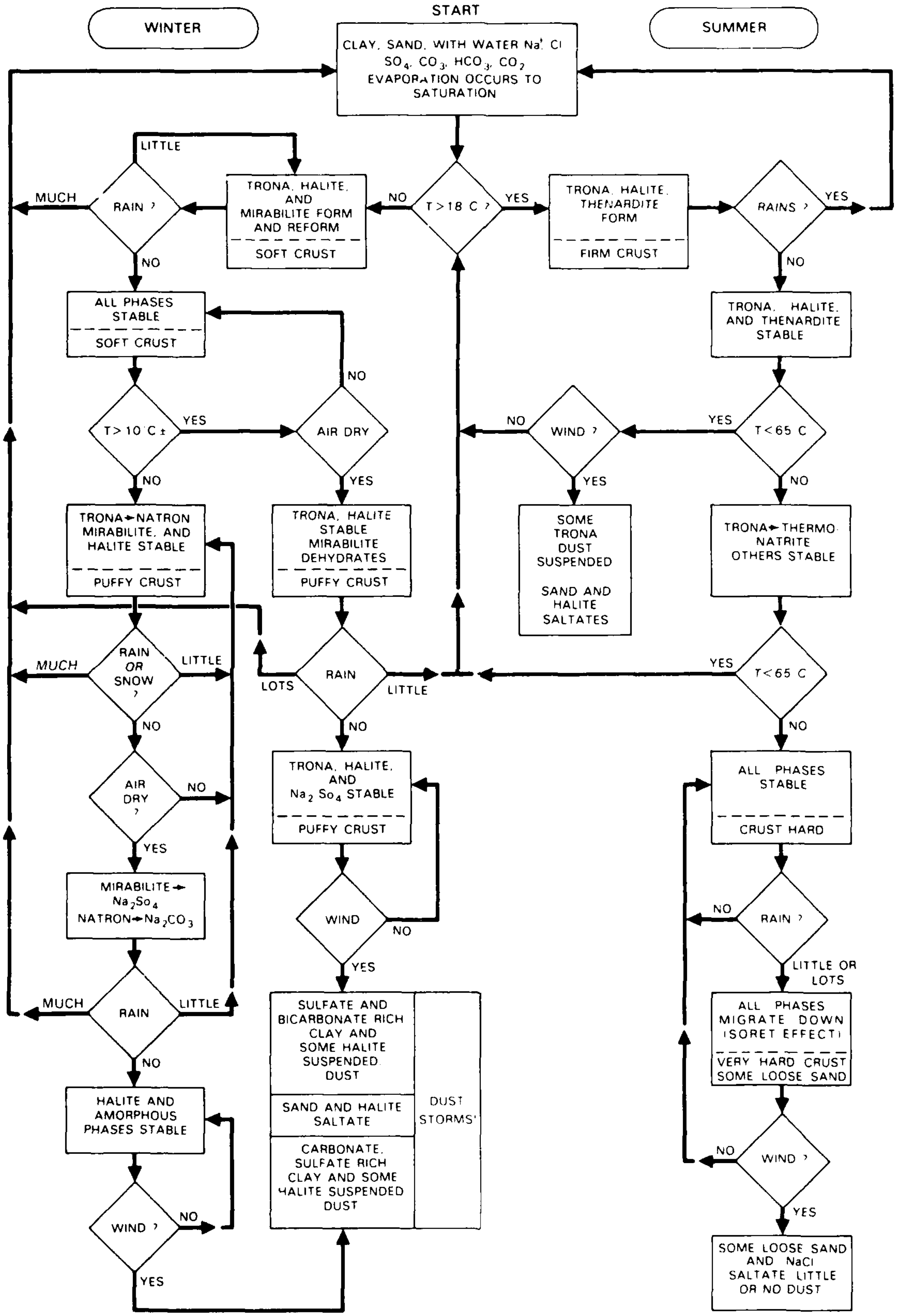


FIGURE 34. Reactions Occurring on the Playa Surface as a Function of Temperature and Humidity.

TABLE 10. Common Compounds Found in Evaporite Deposits.

Name	Composition	Molecular weight	Density	Transition[a]
Burkeite	$Na_6(SO_4)2CO_3$	229		
Gaylussite	$Na_2Ca(CO_3)_2 \cdot 5H_2O$	296	[illegible]	80—H_2O
Glauberite	$Na_2(SO_4) \cdot Ca(SO_4)$	314	2.7	
Halite	NaCl	58	2.2	−20.NaCL·$2H_2O$
Mirabilite	$Na_2SO_4 \cdot 10H_2O$	322	1.5	32.4—H_2O
Nahcolite[b]	$NaHCO_3$	84	2.2	270—CO_2
Natron	$Na_2CO_3 \cdot 10H_2O$	286	1.4	33.5—H_2O
Pirssonite	$Na_2Ca(CO_3)_2 \cdot 2H_2O$	242	2.3	80—$2H_2O$
Thenardite	Na_2SO_4	142	2.7	2.7
Thermonatrite	$Na_2CO_3 \cdot H_2O$	124	2.2	100—H_2O
Trona (Urao)	$Na_3H(CO_3)_2 \cdot 2H_2O$	226	2.1	Decomposes
Sodium-carbonate-dihydrate[c]	$Na_2CO_3 \cdot 2H_2O$	146		
Sodium-carbonate-heptahydrate[c]	$Na_2CO_3 \cdot 7H_2O$	232	1.5	32—H_2O
Sodium-sulphate-heptahydrate[c]	$Na_2SO_4 \cdot 7H_2O$	268	1.4?	Trans to anhydrous

[a] Degrees C at which transition occurs; —H_2O means loss of water. —CO_2 means loss of carbon dioxide.

[b] Probably cannot form on the playa at Owens Lake.

[c] These compounds have not been identified as minerals on Owens Lake; their presence is inferred from chemical considerations.

1965, p. 484), the evaporation of the brine leads to the formation of trona, thenardite, and halite. If enough rain falls, the crust entirely or partially dissolves and the process returns to the starting box.

If little or no rain falls, the minerals are stable and the crust is hard; the clay beneath begins its seasonal drying.If the temperature rises above 65°C, trona becomes unstable and converts to thermonatrite; halite and thenardite remain stable. If the temperature then drops below 65°C, trona slowly reforms. If the temperature does not drop, thenardite, thermonatrite, and halite remain undisturbed unless enough rain falls to dissolve the constituents, whereupon the process returns to the starting box. While summer conditions prevail, the crust is hard and stable (Figure 35), and dust is rarely produced from the playa, regardless of how hard the wind blows. The superficial sand is also cemented into the crust, and, except for sand from loose dunes and from deposits around sand fences and the like, even blowing sand is infrequent.

Summer rains are infrequent; they usually fall in July and August and rarely do more than just wet the surface. The rains can, however, become quite severe, and on rare occasions deposit up to 10 inches of water. Following a slight rain, crystals of all the minerals are found growing on the underside of the crust, presumably because the water washed the solutes there, but more likely because of the Soret effect. Figure 36 shows an inverted piece of summer crust, in July 1985, with crystals growing on the underside. A light rain preceded the picture by about 7 days. The solution near the surface, while warm, is near saturation, but at a depth of a few centimeters, the temperature is near the average annual temperature and the solution is thus saturated, resulting in the precipitation of the solutes there. Sometimes dessication of the underlying soil takes place to the extent that loose silt, dust, and clays are found directly beneath the crust (even though the clay at slight depth may be almost half water by weight).

FIGURE 35. Large Piece of Summer Crust

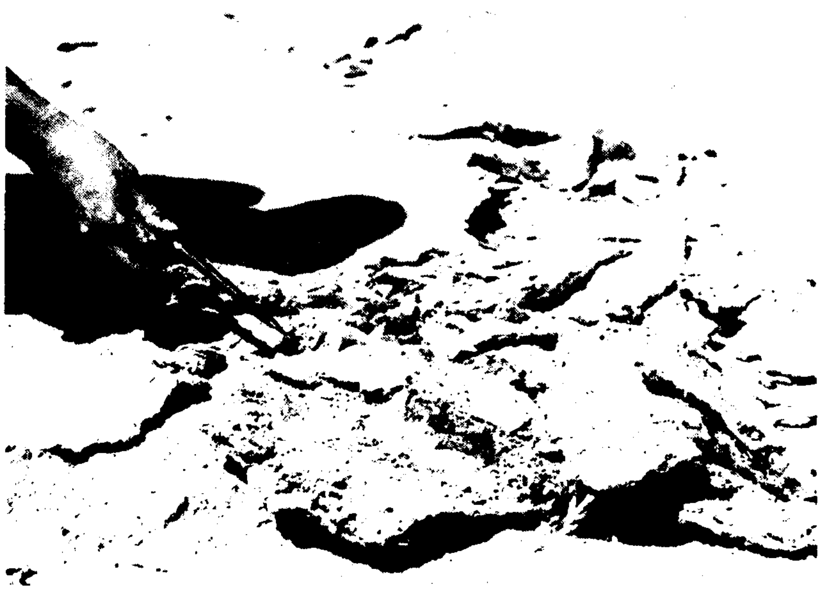


FIGURE 36. [illegible] Piece [illegible] Crust With Crystals Growing on Underside

The winter regime is different. The lower temperatures present in the winter produce a different set of reactions than does the heat of summer. The left hand side of the diagram (Figure 34), shows that, if the temperature is below 17.9°C and above about 10°C (a temperature that depends upon the concentration of the other components of the brine), halite, trona, and mirabilite form (Eugster and Smith 1965, p. 484). If enough rain falls, the alkalis of the crust dissolve and the process starts over. If a little rain or snow falls, then the amount of mirabilite increases. The halite and the trona remain in stable form except for what was dissolved by the rain. The formation of the mirabilite is accompanied by a considerable increase in volume. The mirabilite dehydrates upon exposure to dry air. After several cycles that depend upon rain and wind, the crust is conditioned for production of a sulfate/bicarbonate-rich dust. Throughout the winter regime, it is quite possible that a number of polyhydrates of both sodium sulfate and sodium carbonate form, but we do not have evidence for this at this time.

Should the temperature fall much below about 10°C, the trona converts to natron. Both natron and mirabilite are then present in the crust; both form with an increase in volume and then dehydrate with a concomitant decrease in volume. After several cycles that depend upon wind, rain, and temperature, the crust is prepared for removal of a carbonate/sulfate-rich dust.

The presence of sand is not a prerequisite to the production of dust storms. Observations made on the playa during dust storms indicate that the sand does saltate, and quite possibly helps break up the crust. The upper few millimeters of the farinaceous crust are easily stripped off by the wind, and, consisting as they do of micron-sized particles of the amorphous alkalis, become suspended in the turbulent airflow at the surface. Some particles of sodium chloride are fine enough to become airborne, as is the clay that has been thoroughly disaggregated by the expansion and contraction of the alkalis. The larger particles of salt and the sand form dunes wherever the wind velocity is a little lower or the upward component of velocity is low enough to permit them to settle. A far more important factor in dislodging particulate matter is the presence of large pieces of the lower part of the crust, which become undermined by the wind and are broken off, tumbling over the ground and scarifying the surface. It is quite instructive, although uncomfortable, to watch the process in action.

The effects of cold weather and moisture are dramatically illustrated by the events of early 1986. During January a white crust completely covered Owens Lake bed, except for the brine pool. On 30 and 31 January, an inch of rain fell and almost completely dissolved the entire crust. On 31 January, the alkali crust was dissolved and the lake-bed clays were showing as a dark olive color over almost all the surface. This rain was followed by a few cold days, during which the temperature fell below 0°C. By the morning of 2 February (Groundhog Day), the crust had begun to reform. By late afternoon, some white dust was arising from the extreme southeast corner and from the south side of Owens Lake playa, just seaward of Dirty Socks (see Figure 9). It took but 4 days for the crust to reform. The entire surface, except for the brine pool, appeared as if covered with snow, although none had fallen. The surface was again white. On the morning of 6 February the wind, blowing about 15 knots, picked up dust and carried it over Keeler and Cerro Gordo. Subsequently the wind shifted and the dust was carried southward towards the Indian Wells Valley. The dust originated from the same area as on 2 February, except that there was a good deal more of it. The brilliant whiteness of the dust indicated that it was mainly alkali (probably sodium carbonate) and contained very little clay.

The cold weather during the first days of February probably promoted the formation of the decahydrates of sodium sulfate (mirabalite) and sodium carbonate. These processes take place rapidly when the temperature is low. The rain dissolved the previously formed crust and left a concentrated solution at the surface. While not concentrated enough to produce halite, the solution was enough to permit the formation of the decahydrates. The solubility of halite does not change much with temperature, but the solubilities of mirabilite and natron do. The formation and dehydration of the decahydrates can take place within the space of 2 or 3 days. The wind was quite dry on both days of observation, being adiabatically heated by descent from the Sierra.

Figure 37 shows the concentration as a function of temperatures at which the several compounds precipitate from solution. The solubility of sodium chloride does not change much with temperature; when cold it does not precipitate much more readily than when hot. On the other hand, the carbonates and sulphates of sodium have an extreme variability in solubility because of the formation of hydrates. At or near the freezing point, both natron and mirabilite will precipitate from solutions containing less than 10% solute. Thus, following a rain, crystals of either decahydrate can form on the surface of a still-wet playa and dehydrate to form the amorphous powder that produces dust. A caveat is in order here: because of the formation of hydrates, a certain amount of water is tied up with the compounds, even in solution; therefore the apparent concentration of water molecules will appear to be different with respect to the various compounds because some of the water has been removed from solution. Thus the transition points for a pure solution on any one solute will be different in the presence of the others. Moreover, a number of complex salts may form, which will in turn affect the reactions.

The growth of the mirabilite is accompanied by a large volume increase. If the surface dries off, those crystals of mirabilite near the surface soon loose their water of hydration to the dry air. This gives rise to a powdery amorphous phase, consisting primarily of anhydrous sodium sulfate, with a concomittant reduction of volume. Trona does not so readily loose water of hydration. If no wind blows and more rain falls, the material either dissolves or rehydrates with another volume increase. Each volume change serves to break up the clays and to separate the hard summertime crust into a very soft, fluffy solanchak. Once the salts lose water of hydration, a 15-knot wind can blow away the sodium sulfate, and because the other constituents are no longer held together, the halite, trona, clay, and sand can also be transported.

If the temperature falls to near 10°C, the trona and whatever thermonatrite may be present change to natron. The formation of natron is also accompanied by a volume increase. Once again, if much rain falls, the materials dissolve. If a little rain or snow falls, more of the sodium carbonate and sodium sulfate is converted to the decahydrates. As long as the mirabilite, natron, and halite remain damp, they are stable. In the presence of sodium sulfate, halite forms a dihydrate at temperatures near 0°C (D'Ans 1933), with a slight volume increase, but this is not of great importance in Owens Lake. Once permitted to dry, the mirabilite and the natron quickly loose their water of hydration and both become powdery amorphous masses. The loss of water of hydration is hastened by osmotic transport to the halite. Once the amorphous phases form, removal by wind is easy.

An almost identical process has been described by Juan Puyeo Mur (1979, p. 39) in the ephemeral lakes of the Provinces of Zaragosa and Teruel, Spain. He reports the formation of mirabilite in efflorescences in winter, with subsequent dehydration to a "farinaceous" thenardite, often psuedomorphous after the mirabilite when the crystals of mirabilite have not

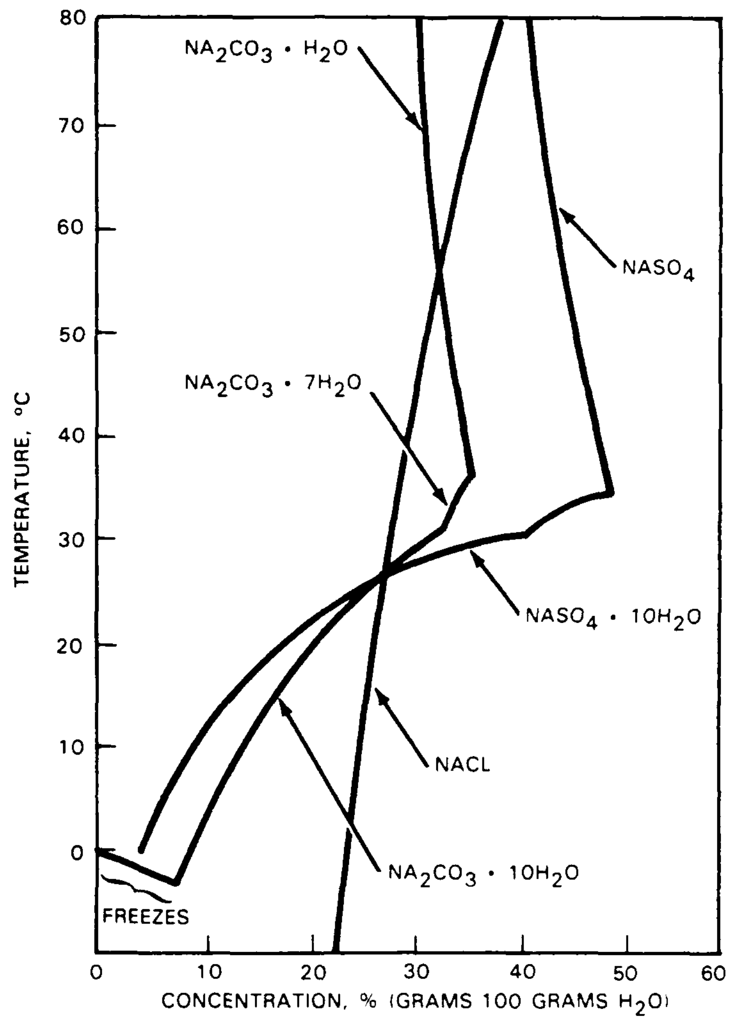


FIGURE 37. Concentration as a Function of Temperatures at Which the Compounds Precipitate From Solution.

been disturbed by the wind during dehydration. He mentions that, because of the microcrystalline structure, the thenardite is easily dispersed by the wind. Because X-ray crystallography shows that the powdery sodium sulfate is amorphous, some question arises as to whether it is properly called thenardite, which has a regular crystalline form. Indeed, X-ray crystallography of the winter crust reveals only halite and silica in crystalline form, although chemical tests clearly show the presence of both sulfate and carbonate ions.

One would expect, because of the temperature dependence of the formation of the decahydrates, to find dust of a different composition depending upon the weather just before the dust storm. For example, the dust of storms that occur in the beginning and at the end of the season might have more sodium sulfate, relative to carbonate, while those occurring in the coldest times might show an increase of the carbonate content with respect to the sulfate. As the season advances and the supply of loose alkali is depleted for that year, one would expect to find a greater percentage of clays in the dust. It would be interesting to check out these conjectures.

Because of the temperature dependence, diurnal cycles in temperature lead to cycling through parts of the process shown in Figure 34. Makrov, as cited by Strakhov (1970) describes a diurnal process at Lake Bolshoi Mormyshanskoe whereby the crystals of mirabilite form by night and change to amorphous thenardite by day. The complex hydrates are quite similar to ice in appearance, and, because of the large amount of water present, are really an impure form of ice. If the temperature is elevated to the decomposition point, they melt, very like ice, and the carbonates and sulfates dissolve in their own water of hydration. They lose water of hydration readily. Were it only for loss of water by evaporation, the increasing molality caused by evaporation would result in decreased vapor pressure, which would in turn cause decreased evaporation. The salts would only asymptotically approach total dessication.

Playas with only sodium chloride usually remain a bit damp and hard throughout the year, except in areas of extreme aridity, such as the Atacama Desert. Playas with sodium carbonate and sodium sulfate often develop a dry surface in cool weather shortly after a rain. Dust storms rarely if ever develop from the surface of a playa that contains only sodium chloride. Because of the extreme lability of the decahydrates, osmotic transfer of salts to the base of such a crystal would raise the exposed surface, which could then dehydrate, causing a further growth of the efflorescence as the season wore on.

VOLUME CHANGE UPON HYDRATION

Thenardite, Na_2SO_4, has a molecular weight of 142.04 and density of 1.464. One mole occupies 53.0 cubic centimeters. Mirabilite has a molecular weight of 322.19 and density of 1.464. One mole occupies 220.8 cubic centimeters. Therefore, an expansion of 4.15 times takes place upon formation of the decahydrate from the anhydrous salt. Upon dehydration, the volume of a given quantity of this material will decrease to 1/4th of the volume of the hydrated salt. Sodium carbonate, has a molecular weight of 105.99 and a density of 2.532. One mole occupies 41.86 cubic centimeters. Natron has a molecular weight of 286.14 and a density of 1.44. One mole occupies 198.71 cubic centimeters. An expansion of 4.75 times takes place upon hydration, and the volume of the hydrated material will decrease to 1/5th of the original volume upon dehydration. Trona, if dehydrate' vould decrease in volume to about 0.75 of the hydrated volume.

The volume change upon dehydration is an important factor in causing the clays to become friable enough to be dispersed by the winds. Firstly, the growth of the hydrated crystals by evaporation of the brines carried up by capillarity and osmosis will result in a considerable volume increase. Secondly, the dehydration of the crystalline material after it has once formed will result in a volume decrease, leaving the clays with considerable voids, and the particles well separated, perhaps even more finely divided, by the growth of crystals in crevices and fissures (Driessen and Schoorl 1973). The wooden tripod in Figure 38 illustrates the effects of crystal growth upon the legs of a wooden tripod situated in a puddle of brine. Not only has the crystallizing alkali greatly expanded the cross section of each of the piers at water level, it has also decomposed the wood.

In summer, the salts forming at the surface are hard and unhydrated because the midday temperatures rise well above the decomposition temperatures of mirabilite and natron. Thus, the firm crust consists of hard crystals of salt and the carbonates and sulfates without water of hydration, or with only minimal hydration, such as the monohydrates. With progressively decreasing temperatures, polyhydrates will reform. We suspect from laboratory experiments

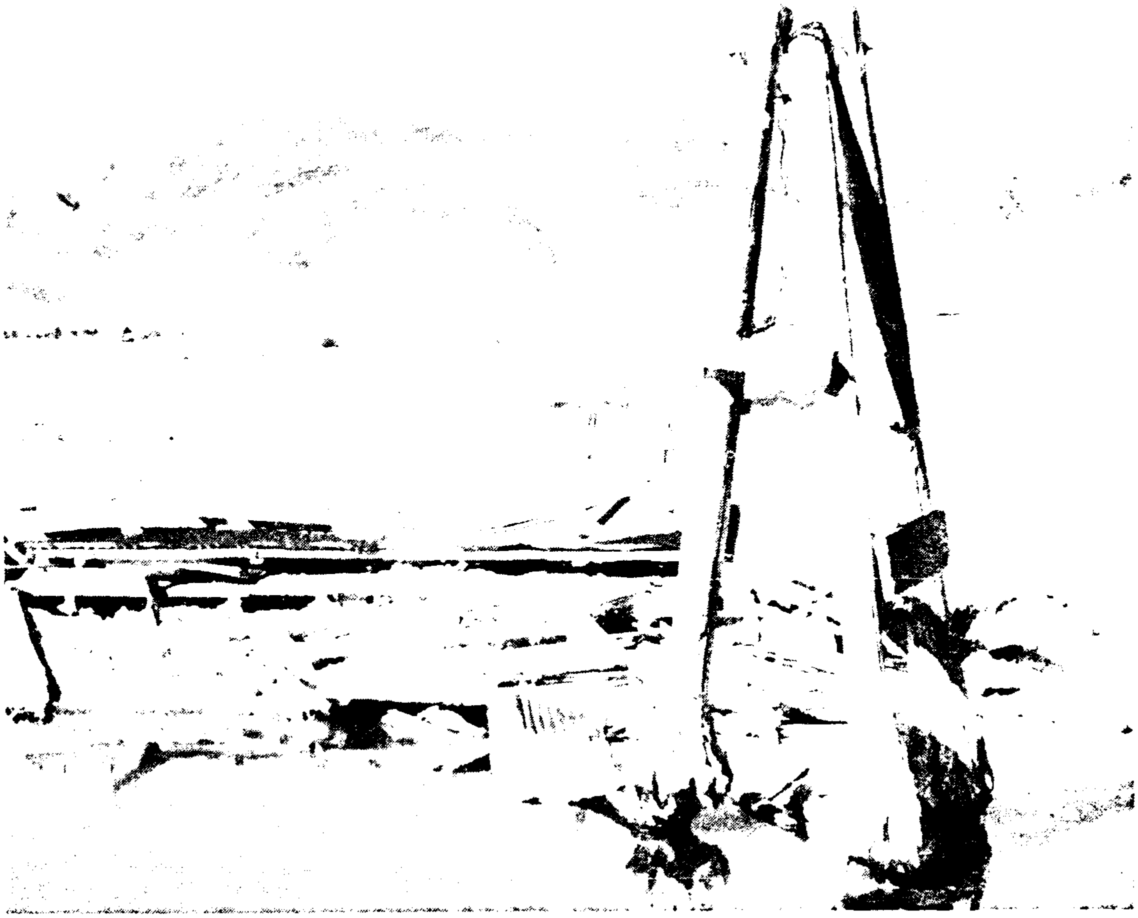


FIGURE 38. Wooden Tripod on Lake Surface Showing Effects of Crystal Growth. Largely Through the Action of Capillarity, the Softer Parts of the Wood Have Been Destroyed and Only the Harder Winter Rings Remain. (Town of Keeler in background.)

that a whole series of multiple hydrates form, depending on temperature. A slight rainfall will result in the formation of hydrates at any season if the temperature is below the dehydration temperature of the materials.

DUST FROM OTHER PLAYAS

It has long been recognized that playas having carbonates and sulfates give rise to dust storms; although the process has not been studied in detail, it has been commented on by a number of authors. C. H. Lee (1913) comments that, as a general rule, efflorescence forms when the water table is less than 10 feet from the surface, but rarely forms if the water table is deeper. D. G. Thompson (1929) makes the same observation and gives a description of almost every playa in California, noting that high groundwater and the presence of carbonates and sulfates contribute to the situation. Bespalov (1951) describes solanchaks in the Gobi Desert, where huge dust storms develop from playas containing mainly chlorides and sulfates.

TREATMENT TO ALLEVIATE THE DUST PROBLEM

No easy solution is likely to be found. Each of the following 11 treatment options for the 110-square-mile lake surface will certainly involve a good deal of time, expense, and effort. Most of them will probably not work. The game is rigged, but if we don't bet, we can't win (W. C. Fields). Any approach, if it is to succeed, must provide some economically useful advantage or some desirable by-products that will make the approach worthwhile, over and above the alleviation of the dust problem.

1. Do Nothing. The removal of the alkali dust by the wind results in a depletion of sodium carbonate, a lesser depletion of sodium sulfate with respect to sodium chloride, and the removal of several tons of clay per minute during the more violent storms. In due time, all the alkalis of importance will be wafted away and the salt will remain, but this will take centuries. Alkali dust will be spread over the entire continent, and the useful components of the dust will be lost.

2. Interfere With the Wind. So far the only attempts that have been made to interfere with the wind have involved putting up dust fences and planting vegetation. No success resulted from these efforts, and there is little reason to expect any.

The basic premise underlying these efforts to interfere with the wind was that blowing sand impacted the surface in the process of saltation and thus dislodged particles of clay and alkali. These particles were ultimately removed by the wind. The alkali is much more easily moved than the sand, which is often cemented into the crust by sodium chloride. Pieces of the winter crust are often undermined and then dislodged by the wind, with the result that these rather large fragments strike the ground, breaking up not only themselves but also the crusted surface (Figure 39).

Sand fences may stop the sand, but they do nothing to prevent the removal of the alkalis and the clay particles. In fact, by increasing the turbulence near the ground, they may actually increase the rate of removal of the smaller fractions. Were enough of the 110-square-mile lake bed covered by sand fences, in an intermeshing pattern so as to be effective in stopping sand regardless of wind direction, it might ultimately be possible to increase the thickness of sand on the entire surface to discourage the development of the solanchak crust. This process would be very costly.

3. Cover the Playa With Sand. A layer of sand upon the surface would slow the upward movement of the saline groundwater by capillarity, but unless the layer were several feet thick, it would be just a matter of time until the salines were at the surface. One consequence might be the formation of hard crystalline layers of the evaporites at the base of the sand. Such layering is noted around the present water body in places near the delta of the Owens River, where loose coarse sand covers the surface to depths of a few feet. If the sand were to be placed upon the surface, it might then be possible to start some shallow rooted vegetation to stabilize the sand because the vegetation could begin to grow by using water brought upward into the sand through vapor-phase transport. The sheer volume of sand required, which would amount to at least 200,000 acre-feet (roughly 2 billion metric tons), makes this idea less attractive, unless the sand could be trapped and held by the sand fences: a most unlikely event. If the water table were to remain high or the lake flooded, the sands would then become saturated with the alkalis, and the crust would grow on the top of the sand in spite of the reduced capillarity. The success of this system would have an adverse effect upon the recovery of the sodium compounds from the lake.

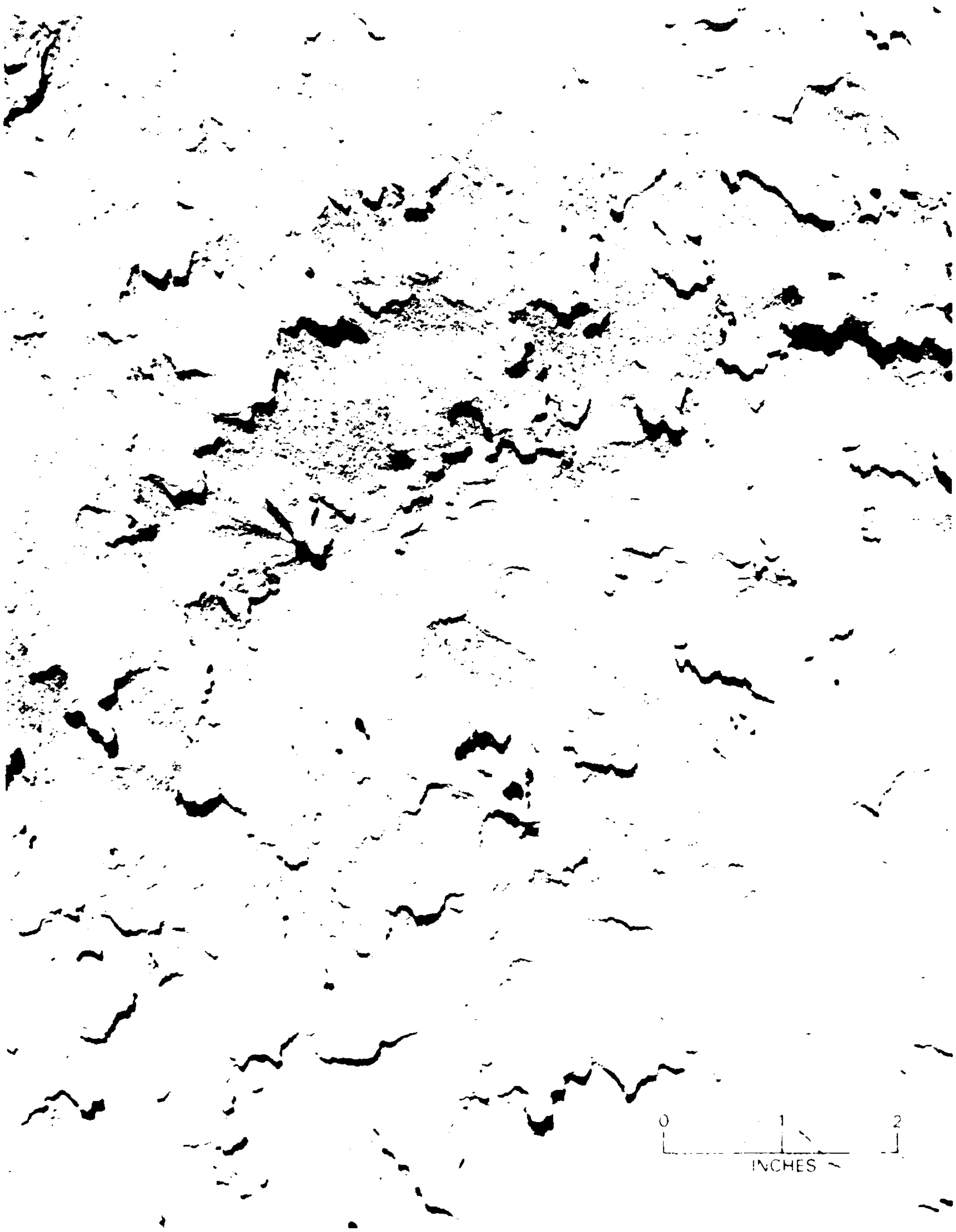


FIGURE 39. Section of Winter Crust Undermined so as To Allow Dislodgment of Large Pieces by the Wind

4. Encourage Vegetation and/or Revegetation. The whole of the playa is contaminated with the various alkalis and with salt, but it might be possible to find some vegetative cover that could survive on the surface. This would be an attractive solution, except that the soil contains enough boron to preclude use of even the most halophytic plants.On the other hand, where an artesian well or spring has been permitted to overflow the surface, grasses and other vegetation do well all year round. This tells us that the soil can be cleaned and the more toxic elements removed, offering a possibility for stabilization of at least a part of the surface. Were an option of this sort to be tried, it would be necessary to take steps to ensure that future flooding of the lake surface by deliberate dumping of water would not occur. A useful by-product would be the development of limited agriculture or livestock grazing.

5. Flood the Playa. It is often suggested that the surface of the lake could be flooded and kept damp. If enough water were available to totally refill the lake to the 1913 level or thereabouts (approximately 2,400,000 acre feet, not counting the ensuing groundwater recharge), the water might well prevent the major dust storms. Some smaller storms would develop on areas peripheral to the lake where efflorescent crusts would develop after a time. It would take more water to flood the playa and maintain it in a wet state than is now available. The surface would require at least 10 feet of water a year to compensate for evaporation and keep the surface wet. This would be a waste of between 300,000 and 700,000 acre feet of potable water that can not be spared. Any attempt to keep the surface slightly moist would result in an exacerbation of the problem, in that it would cause more growth of the alkaline crust.

6. Coat the Playa. It has been suggested that the surface of the playa could be coated with some sort of membrane, asphalt, or other material that would prevent evaporation. This might work if it were possible to prevent the destruction of such a surface by the growth of crystalline precipitates and the action of the sodium carbonate. The cost would be enormous, and the actual work would have to be preceded by several years of careful research to find such a material.

7. Treat With Chemicals. It has also been suggested that limestone or similar material be placed upon the surface to cause it to become harder. It might be possible to apply calcium sulfate, which might eventually turn to calcium carbonate and form a harder surface, but it would be only a short time until that crust was also broken up. Adding limestone or gypsum to the surface might also result in the formation of complexes of sodium and calcium carbonate and sulfate, and this might aggravate the situation. To try a test plot with this treatment, however, would be useful.

8. Stabilize the Blowing Sand From the Lake Shores. A treatment to prevent the blowing of sand from the northern and southern shores of the lake and to keep the sand dunes from migrating back and forth is within the realm of ordinary reclamation efforts. There seems to be no pressing reason to do this now. The dust will be dislodged, and dust storms created, with or without the sand.

9. Clean the Playa by use of Polders. Sidney S. Alderman, Vice President of Agricultural and Industrial Minerals, Inc., of San Carlos, California, has suggested that a system of polders be developed to wash the alkali from the surface soils into the sump at the western side of the lake (Alderman 1980). This is the technique used by the Dutch to clear the soil of Holland of sea salt. It could work, but the cost of ringing the lake with such a system of dikes would be high. In 1980 Alderman calculated a cost of $25,000,000 over a period of 15 years.

In concentric strips around the north, east, and south sides of the lake, fresh water impounded behind dikes would percolate through the lake bed and be picked up in drainage ditches after having dissolved the alkali salts and leached them from the soil (Figures 40 and 41). This water would then be pumped by windmills into the sump where it could evaporate, leaving the solids behind.

The water to do this would come from water now entering the playa area from around the sides. Some 80,000 acre-feet a year of good water is now lost by evaporation. This water could be pumped into the polders and then removed to more down-slope polders, or put directly into the sump. Once an area were cleared of enough alkali, some sort of vegetation could be made to grow, temporarily at least, in that part of the surface and the land could be used for livestock.

This scheme would concentrate about 150,000,000 metric tons of sodium products, worth about 4.5 billion dollars, on the west shore of the lake where they could be recovered. This amount of salines would, not counting water of solution and of hydration, fill the lower part of the lake to at least the 3,553 foot contour (Figure 40).

10. Lower the Water Table. As has been noted by David Thompson, C.H. Lee, Willis Lee, and many others, efflorescent crusts do not develop on playa surfaces where the depth to groundwater is at least 10 feet below the surface. Following the removal of the surface alkalis by leaching, and transport into the sump, it would be advisable to lower the water table to at least 10 feet below the surface. This lowering could be accomplished with a set of windmills that could remove the water from sand layers beneath the playa surface—as some of the artesian wells, even in the center of the lake, do at present. The clays are but poorly permeable and will not yield water readily, although—given enough time—they would dewater into the underlying sandy sediments. If the water table could then be established at 3,555 feet at the edge of the water body, and permitted to remain at least 10 feet beneath the surface from there to the edge of the playa, the dust problem would ameliorate within a decade or two. Once the polder system had cleaned the surface, the natural evaporation would help lower the water table, even if pumping were confined to areas peripheral to the playa itself.

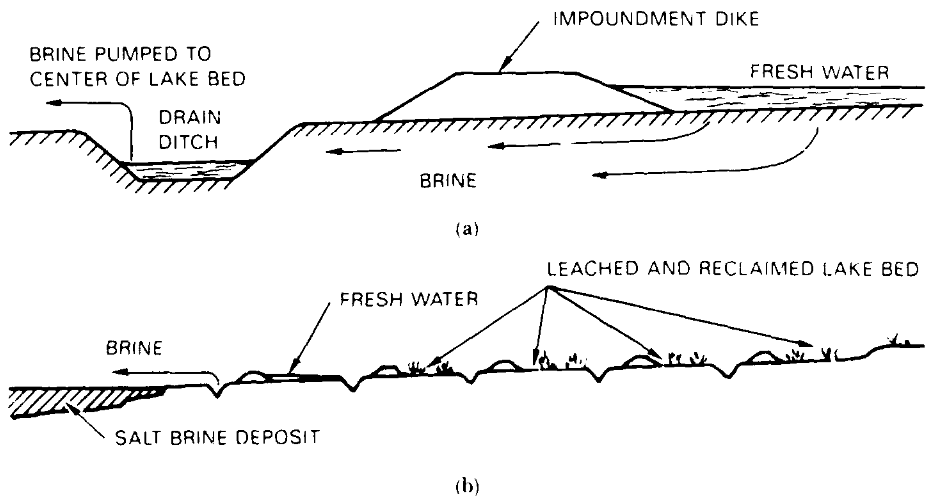


FIGURE 40. Polder System: (a) Operation of Single Dike and Drain Ditch, and (b) Section Through Center of Lake Bed with Multiple Contoured Dikes and Ditches. (After AIM Inc., 1984.)

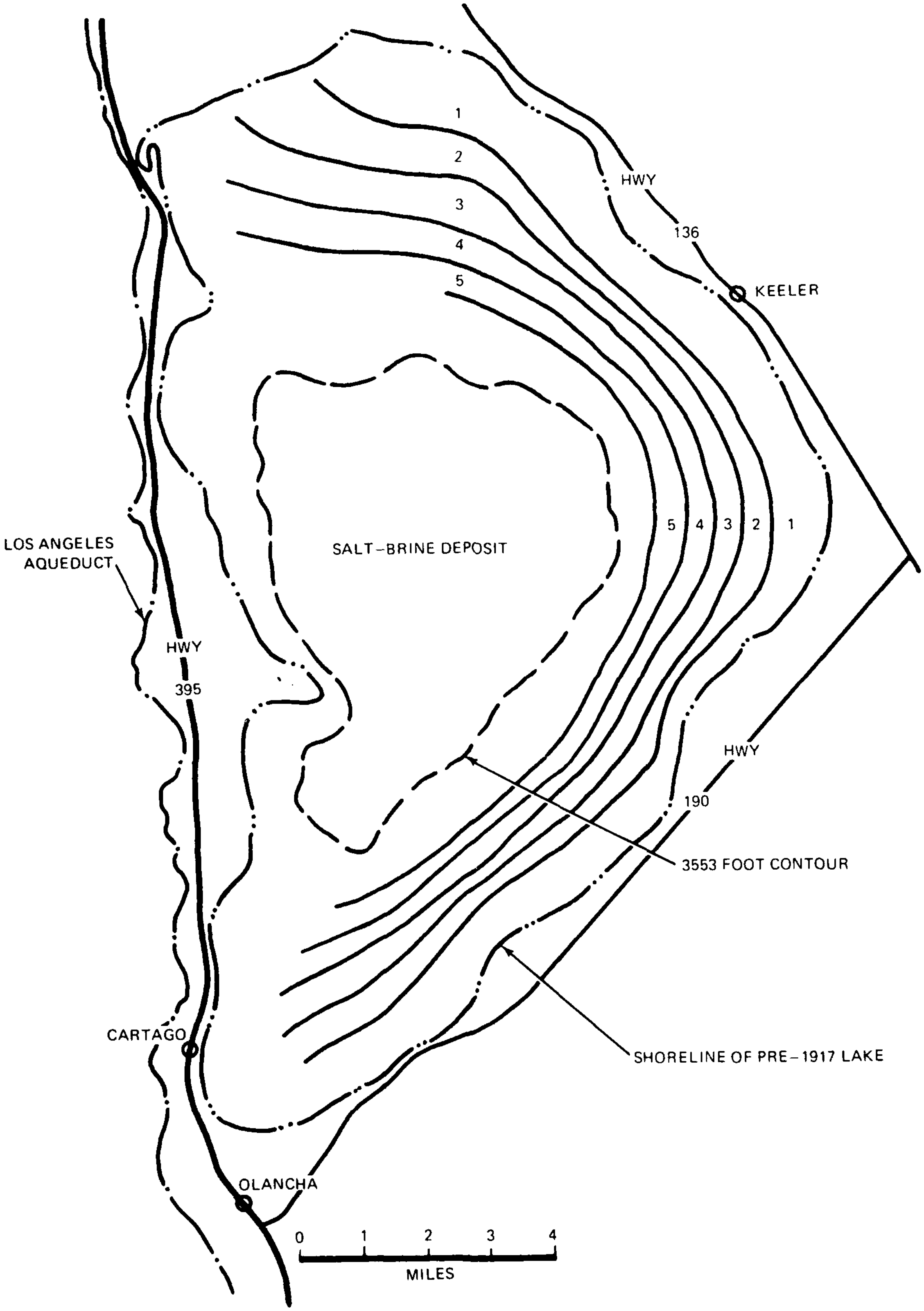


FIGURE 41. Owens Lake Bed Showing Location of Concentric Strips for Polder System.

Following the lowering of the water table, some of the water that accumulates in the springs around the lake, as well as that which flows south into the playa along the course of the Owens River, could be used locally for irrigation or exported for use elsewhere, such as the Indian Wells Valley, where it will soon be needed.

11. Combine Polders With Groundwater Lowering. The concept of lowering the water table is sound enough by itself, although it would yield an enormous mass of water that would have to be disposed of in some way. Initially, about 70,000 acre-feet of dilute brine would have to be removed, and subsequently about 70,000 acre-feet per year would have to be pumped. The advantage of the polder system is that it gives an excellent means of evaporating the water while developing a saleable by-product. If the domestically useful water were to be used locally or exported, another benefit would accrue. However, any attempt to export more water from Owens Valley is likely to lead to public-relations problems, unless the matter is clearly explained beforehand or unless it can be shown that the water's export would benefit the local folks.

The option of using polders combined with groundwater lowering is attractive. It would be worthwhile to try a pilot plant approach, using several square miles as test areas.

SUGGESTIONS FOR FURTHER WORK

Although we feel that we have made a good start toward understanding the mechanisms of dust storm development, we feel strongly that much more can be done. It is not necessary to consider only the practical aspects of this particular problem; a myriad of opportunities for doing useful research lie untouched, beyond our ability to look into them. A few examples follow.

- A more careful analysis of larger dust samples taken throughout the year would lead not only to a better understanding of the seasonal nature of the mechanism but also to a determination of the chemical composition of the dust as a function of the weather.

- A careful distinction should be made analytically between the presence of sodium carbonate and the presence of sodium bicarbonate.

- More detailed analysis of cores should be done, with determination of the water content and chemical content of the cores as a function of depth. Cores should be taken to considerably greater depths than we could attain.

- It is time to revisit the problem of determining the evaporation from playas as a function of temperature and season of the year. The isolation of the upper surface of the playa by formation of the crumbly clay section certainly decreases the capillary conductivity of the surface layers to the point that loss of water from the playa may actually be less in summer than in winter. This work would lead to reassessment of the recharge rates of desert basins that were made by estimating the evaporation from playa surfaces.

• A theoretical and experimental study to determine the effects of osmosis on the upward transfer of solute in cold weather, when osmosis and capillarity both act in the same direction, might lead to further understanding of the processes in saline environments. The total evaporation rate from clay-covered surfaces may be greater than heretofore thought.

• The concentration of trace compounds such as nitrates might be controlled by tiny differences in osmotic behavior and solubility. It is not by accident that the only nitrates found in surface deposits are encountered in regions where rainfall is scant. The extreme solubility cannot alone be the answer. The nitrate deposits in California are all encountered in the dissagregated surface of a hard claystone, immediately above the less weathered portion of the clay. More than likely the nitrates were washed down from the more superficial layers; but it may be possible that the underlying clay exerted an osmotic attraction on such rain water as wet the interface between the disaggregated clays and the hard claystone, removing the water from the nitrates solutes and thus hastening their drying.

• The study of the development of the crumbly surface on top of the clay during the course of a year and the effects of this layer upon evaporation would make an interesting doctoral thesis.

• Deep coring of the playa would yield considerable information on past climates. It must be done with more than ordinary care in order not to overlook periods of dessication of the the lake.

• A careful sectioning of the surface crust should be made at regular and frequent intervals throughout the year and following rainy periods and other weather conditions so that the actual distribution of the compounds as a function of their vertical position can be determined.

• Test plots using different surface treatments would be worthwhile to see the effects of adding other ions to the melange.

• The locality is ideal for studying the effects of saltating sands. Collectors could determine the "scale height" of the moving sand as a function of height above ground and particle size. The long fetch available would make a useful experiment possible, especially if it were accompanied by use of devices to adjust and regulate the wind flow.

• Ample opportunity exists to study means of stabilizing sand by use of vegetation or other techniques.

• Opportunity exists to consider the development of halophytic plants for land reclamation purposes and to develop boron-tolerant species, if such be possible.

• Owens Lake would be a fine site to study the effects of vibration on clays and to determine how clays could be mobilized for engineering purposes.

This list could go on indefinitely. We will probably not be able to return to this problem or to do as much as this interesting and valuable area would tempt us to. Others will, we hope, find it worthwhile to rise to the challenge.

COMMENTS ON DESERTS

It is well to try to learn how to handle situations such as the dust problem on Owens Lake. Some new thinking and considerable effort is needed. Any process by which land is returned to some reasonable use that is itself adapted to the climate can yield benefits to humanity at large, since large portions of the earth's surface are now virtually useless for agricultural purposes. As the drying trend of the last 9,000 years continues, more land will be added to the world's deserts. Land now held to be useful or marginally useful will become much less so.

Attempts to put deserts into agricultural production, without the importation of water, have been notably successful, but only for a short time. Whenever the water balance of a region is disturbed by massive use of groundwater, in excess of recharge, the same thing has happened: the culture that has depended upon the locally supplied irrigation expands far beyond what can be supported for a very long time and eventually collapses. The groundwater is soon used up, leaving dessicated fields from which even desultory breezes remove soil.

This process has been rampant in India for the last century. The Rahjastan Desert is now growing by kilometers per year. The air pollution resulting from the removal of dust from that surface approaches 5 tons per square kilometer. This pollution has in turn changed the weather. As the situation worsens with the passage of time, and with nothing done to correct it, the desert will eventually spread throughout the whole of the Ganges plain.

In Eygpt the annual floods of the Nile have now been controlled by the High Aswan Dam, with the result that groundwater recharge has been reduced downstream. The soil has been deprived of its annual enrichment, and large areas of salinization of the top soil have developed. Worse, during the post-war period, exploration led to the discovery of vast quantities of groundwater beneath the Sahara. This soon led to increased agricultural development, which some 40 years later has resulted in the depletion of most of the groundwater and a serious decrease in the arability of the land. Well-meant plans that do not consider long-term factors often lead to unforeseen consequences that make matters worse.

Lake Aral is a brackish water body in southwest central Soviet Asia, with an original area of about 26,000 square miles. Withdrawal of water from the Amu and Syr Dary'ya Rivers has caused the level of the Aral Sea to drop some 10 meters between 1975 and 1984. Dust storms are developing from the northeast shores of the lake and from the dessicated lake bottom. Streams of dust up to 500 kilometers in length and 4,000 meters in height have been noted in satellite photographs. The dust particles appear to be mainly in the 1.75 to 4.2 micron size range (Kondratyev et al. 1985).

Whenever the consumptive use of water exceeds the annual recharge, trouble develops. Taken out of context, the famous quotation from Isaiah (35:1), "The wilderness and the solitary place shall be glad for them; and the desert shall rejoice, and blossom as the rose," has lead to widespread hope—and justification—for development of desert regions. The desert may indeed be made to bloom as a rose, but only until consumptive use of water exceeds the sustainable perennial yield—unless water can be imported from some water-rich region, which is the opposite of what is happening now in Owens Valley.

The situation in Owens Lake, originally created by local irrigation projects and aggravated by export of water to the City of Los Angeles, would have developed in any case with the passage of time as the climate continued to dry. If, on the other hand, the rainfall were to increase for a protracted period, even with water export, the lake might refill. To bring this about would take only a change from a 5-inch-per-year rainfall to a 10-inch rainfall. As it is, in the odd year when rainfall is abundant, the LADWP dumps water into the lake partially filling it.

The certain recurrence of protracted rainy periods will once again fill the lake, perhaps not to overflowing, but certainly enough to change the nature of our problem. Such events have occurred within the last 2,000 years, when, for example, the north playa of Panamint Valley was filled by runoff from its own internal drainage. This point is being dramatically demonstrated in Utah, where Great Salt Lake is filling beyond its banks and creating a situation that may or may not be correctable, and correctable only at enormous cost. This makes it necessary to consider that any surface treatment not be such that it would create other problems in the event of a refilling of the lake by runoff. This comment would also apply to any desert playa in the western United States that might be considered as a logical place for a waste dump.

The Owens valley has a series of problems of unbelievable complexity that derive from the peculiar way law is generated in California. During a series of lawsuits in the 1930s and 40s, the Natural Soda Products Co. was trying to prevent the LADWP from releasing water into the lake bed. The reason for dumping the water is that the water flow is needed to produce electricity and that storage farther down stream can not receive the water fast enough to sustain the electrical production. The soda company was informed that not only was Los Angeles permitted to dump water into the lake, it was obligated to do so because that is where the water would have gone if it had not been diverted in the first place (Kahrl 1982, p. 378 et seq.). This sort of policy, based on legalistic reasoning, is not likely to lead to a sensible development of the water resources of a region or to the solution of environmental problems, and is certain to cause economic hardship and discontent. The courts eventually found that the Natural Soda Products Co. should be compensated for damages to their plant.

California water law is complicated and difficult to understand or to apply. Intrusion into the scene of federal agencies and district regulatory bodies does little to clarify the law. In 1906 President Roosevelt decreed that the water taken from Owens Valley could not be sold to anyone outside the Los Angeles area. In 1945 a new California statute prohibited the wasting of the water from Mono Basin and Owens Valley by the LADWP. In 1950 the courts once again permitted the LADWP to release even more water into the lakebed than the LADWP had in the Natural Soda Products case, but only after all reasonable attempts had been made to use the water. Each addition or amendment to California's water laws has been promoted by special interest groups, to meet a particular perceived threat or need, without regard to the total impact of this collection of conflicting provisions. The problem is aggravated by such draconian decisions as the Supreme Court's distribution of Colorado River water, which allocated vast quantities to Arizona and thus created great difficulties for Southern California.

The problem involving Owens Lake is further complicated by accident of ownership. Originally the lake and the river were under control of the Army Corps of Engineers because

the lake and river were navigable waterways. Subsequently, the lake was given to the California State Lands Commission, which leases portions of it to various groups. The dust problem, therefore, properly belongs to the State of California—even though the LADWP usually gets the credit for it. So far, the level of cooperation between the several agencies involved has been high, and the state legislature has tried to help by passing acts granting money to build sand fences, etc.

We have no doubt that the production of the dust can be controlled. We are also sure that such an effort will be of great benefit elsewhere. To accomplish this end, an eclectic approach to the problem is necessary, and only the willing, whole-hearted cooperation of the several agencies involved can make this possible. In the years since our first paper on the subject appeared (Reinking et al. 1975), a new attitude of wholesome cooperation has emerged. It must continue.

Intelligent use of the desert has untold benefits for mankind. Careless use of the desert is certain to lead to a worsening of worldwide conditions. We are looking at an example of such practice in Owens Valley and the Mono Basin. By learning how to cope with the problems that arise, it may be possible not only to rectify those situations, but, on a larger scale, to improve conditions elsewhere to the point where some marginal regions of the earth's surface may become useful again. Climate depends upon land use, as land use depends upon climate. It will be a challenge for future generations to master this interaction and to bring about better use of the earth.

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The geochemistry was worked out in detail by Camille Gaines during her visit to NWC as a summer student; her logic diagram helps in understanding the dependence of the storms on weather conditions. Professor David Rein worked with us on the hydrology of the lake. Perrie Barnes helped us research the history of Owens Valley. Gene P. Saint-Amand and David C. H. Saint-Amand accompanied us on many field trips, took photographs, collected data, and dug holes.

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Although we have shamelessly borrowed from these and many others, we do not mean to imply that all or any of them agree with all or any of this paper. One's point of view sometimes depends on one's interests. We have tried to avoid making pejorative comments, rekindling old disputes, or drawing moral conclusions. We hope that the contents of this paper will enable others to go ahead, develop a better understanding of the dust problem, and more effectively deal with government agencies in putting the problem, further research, and possible solutions into clearer perspective.

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GLOSSARY

Advect—To carry into an area, as of a stream of air being moved into a region by large scale circulation patterns.

Aeolian—Windblown, as with sand brought in by the wind. Named for the Greek god Aeolus, ruler of the winds.

Adiabatically—Referring to the compression or expansion of a gas without exchange of energy with its surroundings. Adiabatically compressed air is warmed because the same amount of energy occupies a lesser space; thus air brought down a mountain slope by the wind is warmed. Air that rises adiabatically is cooled as it goes up.

Alert level—One of several levels of concern over air pollution as defined by the Environmental Protection Agency.

Alkali—One of several univalent metals such as sodium, potassium, or lithium whose oxides and/or carbonates are markedly basic. From the Arabic "Al-qili," the ashes of a plant formerly grown to produce alkalis for soap making. Tumbleweed, *Salsola kali*, was also formerly grown for this purpose.

Alkali earths—The oxides of any of several divalent metals such as calcium, strontium, and barium that produce strongly basic reactions.

Alkali-earth chlorides—Chloride salts of any of the alkali earths. These salts are usually quite soluble and very hygroscopic.

Amorphous—Without crystalline structure.

Anhydrous—Not containing water as a bound chemical entity.

Artesian wells—Also called flowing wells. Wells in which water comes to the surface without pumping. The hydrostatic head for such water is above ground level, the water being held down by some impermeable layer of clay or other material through which it cannot penetrate.

Biota—The fauna and flora of a region.

Capillary—A narrow space in which liquid can rise because of molecular attraction to the sides of the space. As an adjective, it describes the process by which liquids can rise in a solid because of molecular attraction of the solid for the liquid. Capillary rise is inversely proportional to the square root of the particle size in sediments, hence on the order of feet in clays and inches in sands.

Circulation—Any movement in a rotary fashion, or, less precisely, any mass movement such as the movement of air in weather systems.

Clastic dike—A crack in soil or rock that has been filled with other material that entered the fissure. Clastic dikes in the lake bed are usually of sand that has fallen or been washed into openings in the clay of the playa surface.

Crust—The hardened upper surface of almost anything, here applied to the accumulation of alkaline and saline materials on the surface of the playa.

Cyclogenesis—The development of a cyclone, or storm system, caused usually by interaction with rising ground or by exchange of heat with the surface. Any tendency of a storm to intensify as it goes along.

Dihydrate—A chemical compound that has two molecules of water attached to one molecule of the parent material. Thus, sodium chloride dihydrate has the form: $NaCl \cdot 2H_2O$. The chemical properties are not usually changed much, but the density and other physical properties are

Evaporation ponds—Ponds constructed for the purpose of isolating a quantity of liquid so that the water therein can be evaporated in order to concentrate the salts dissolved in the water. Used for the production of soda and salt. Also called evaporators.

Evaporites—Minerals formed by evaporation of water from lakes, seas, or other bodies such that beds or the evaporites remain behind.

Fanglomerate—Rocks, gravels, and sand that have been deposited in an alluvial fan and have since become cemented into solid rock.

Fetch—The distance along open land or water over which the wind blows.

Flowing wells—(see *Artesian wells*)

Graben—A block of land dropped down between two faults. The opposite of a horst.

Great Basin Air Pollution Control District—A governmental agency responsible for measuring the purity of the air and for taking corrective measures to prevent its contamination.

Heat sink—Any body of material that can adsorb large amounts of heat, usually preventing a large temperature rise in the process.

Hydration—The addition of water molecules to a chemical compound.

Ion—An electrically charged atom or molecule. When a solid capable of disassociation—such as salt—dissolves, the molecule splits into ions. Some substances, such as sugar, do not split upon solution and do not produce ions.

Lake basin—A basin that contains or formerly contained a lake. Usually a closed depression, such as Owens Valley.

Lake brine—Any solution of salts dissolved in water in a lake. The term usually refers to a rather strong concentration.

Laminar—Anything in layers, from the Latin "lamina," layer. Laminar flow is nonturbulent flow, as applied to the wind when the air is thermodynamically stable.

Lapse rate—The rate at which the temperature of the air "lapses" or changes with altitude. As air rises it is cooled; as it descends it is warmed, usually about 2.2°C per 1,000 feet in cloud-free air.

Millibar—One bar is the pressure of the atmosphere under standard conditions at sea level, about 14.7 pounds per square inch. A millibar is one one-thousandth of a bar. A unit used in preparation of weather maps.

Multiply offset—Displacement of any geologic feature in more than one locality by a fault.

National episode criteria—A set of criteria produced by the Federal Government to describe episodes of air pollution or other types of pollution.

Orographic—Having to do with a mountain or mountains. May refer to winds, clouds, or other weather situations.

Osmosis—A process whereby liquids will move to a region where the concentration of a salt is greater, or by which the molecules and/or ions of the salt will move toward a region of lesser concentration.

Particulate load—The weight of solid material suspended as particulate matter, either in gases or liquids. In air pollution, the particulate load is usually expressed in micrograms of solids per cubic meter of air. It may also be expressed in tons per unit area, such as tons per square kilometer or tons per square mile.

Playa—Spanish for beach, applied to dry desert lakes because they are all beach. In Spanish it may also mean seashore.

Polder—A track of land reclaimed from a body of water.

Rotor—A term used to describe a horizontal whirlpool that develops in the lee of steep mountain slopes when the wind velocity aloft is high and is usually increasing with altitude. When these violent rotors touch the ground, the wind direction may actually reverse locally, and sand and small gravel is often lofted to considerable height. Turbulence in rotors is quite hazardous to aircraft; the wind on one side may be going up several thousand feet a minute and down at an equal rate on the other side.

Lake Russell—Ancestral Mono Lake. During Pleistocene, Mono Lake occupied about five times its present area. The ice age lake has been named Lake Russell for Isreal Russell, who first described the area for the Geological Survey.

Saltating Sands—Sand particles being moved by the wind in a series of short leaps or bounces.

Septahydrate—A chemical compound in which seven molecules of water are attached to one molecule of the parent compound.

Silica Gel—A gelatinous solution of sodium silicate. Formerly used for preserving eggs.

Solanchak—From Russian, a sodium-rich soil. Usually refers to the puffy "self-rising" surface of saline desert playas in which clay particles and sand are mixed with the alkalis.

Solanetz—From Russian, a bluish-black sodium-rich soil in which organic material has been reduced by the action of sodium carbonate to relatively pure carbon.

Soret Effect—From "Le effet Soret," a French term for a process whereby dissolved solids will move in the direction of a temperature gradient. Thus in hot weather, salts will move downward toward cooler soils just below the surface, and in cold weather such salts will move toward the surface because it is warmer below.

Synoptic Situation—Meteorological term used to describe the weather conditions over a wide area.

Tioga (see Wisconsin)

Total loading—The total of all suspended particulate material above an area.

Wisconsin—The most recent of the four major glacial advances during the ice age. It began about 24,000 years ago and ended about 9,000 years ago. In the west it is called Tioga.

Zonal airflow—Usually refers to the westerly winds developed during fall, winter, and spring, in which the wind flow is roughly parallel to the pressure field, running from west to east.

Sulphate plant—People from the Owens Lake area refer to a collection of loading ramps, wells, and other debris in the central playa, reached by a road from the east side of the lake as the "old sulphate plant." It was formerly serviced by a railroad and has an artesian well associated with it.

Lake workings—Usually refers to the operations of Lake Minerals Corp. on the west side of Owens lake, near the brine pool.

Pittsburgh Plate Glass Co.—A producer of plate glass that formerly operated an elaborate soda and borax recovery operation near Bartlett's Point on the west side of Owens Lake. Production ceased in the 1950s because the level of the water in the lake could not be stabilized.

Westec area—An experimental plot, reached from the Lake Minerals compound on the west side of the lake, where the Westec Company attempted vainly to stabilize the dust through the use of snow fences and the planting of shrubbery.

Xerophyte—A plant that is structurally adapted for life with a limited water supply.